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CANVAS: A Canadian behavioral agent-based model for monetary policy ☆

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A B S T R A C T

We develop the Canadian behavioral Agent-Based Model (CANVAS) that complements traditional macroeconomic models for forecasting and monetary policy analysis. CANVAS represents a next-generation modeling effort featuring enhancements in three dimensions: introducing household and firm heterogeneity, departing from rational expectations, and modeling price and quantity setting heuristics within a production network. The expanded modeling capacity is achieved by harnessing large-scale Canadian micro- and macroeconomic datasets and incorporating adaptive learning and simple heuristics. The out-of-sample forecasting performance of CANVAS is found to be competitive with a benchmark vector auto-regressive (VAR) model and a DSGE model. When applied to analyze the COVID-19 pandemic episode, our model helps explain both the macroeconomic movement and the interplay between expectation formation and cost-push shocks. CANVAS is one of the first macroeconomic agent-based models applied by a central bank to support projection and alternative scenarios, marking an advancement in the toolkit of central banks and enriching monetary policy analysis.

1. Introduction

Economic models play a pivotal role in the policy-making process of central banks. They aid policymakers in understanding economic developments, evaluating policy options, assessing risks, and projecting main macroeconomic variables such as GDP and inflation. Ever since the seminal work by Smets and Wouters (2003, 2007), New Keynesian DSGE models that employ Bayesian estimation techniques have been shown to exhibit a similar forecast performance to comparable time series models (Del Negro and Schorfheide, 2013). These DSGE models have become the workhorse framework for central banks and other institutions to engage in economic forecasting and policy analysis on a sound theoretical basis and have been regarded as a minimum standard when it comes to studying business cycles in a general equilibrium framework (Christiano et al., 2018; Brunnermeier et al., 2013). There are

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limitations of traditional economic models, however, in addressing topics like heterogeneity, departure from rational expectations and various forms of nonlinearities.

To complement these models and bridge some identified modeling gaps, some economists have been advocating agent-based models as a new, promising direction for macroeconomic modeling.[1] Farmer and Foley (2009), in particular, suggest that it might be possible to conduct economic forecasts with a macroeconomic ABM, although they consider this to be ambitious at the time. Over the decade after the 2008-2009 global financial crisis, several macroeconomic ABMs have been developed featuring a more clear common core of macroeconomic agent-based models as in Dawid and Delli Gatti (2018).

Haldane and Turrell (2018), for example, suggest that ABMs can be complementary to existing approaches for answering macroeconomic questions where complexity, heterogeneity, networks, and heuristics play important roles. More recently, Delli Gatti and Grazzini (2020) advanced the approach to take ABMs to the data by combining Bayesian estimation of key parameters and forecasting of aggregate macro variables in a medium-scale macro ABM. A recent survey by Axtell and Farmer (2023) and work by Dosi and Roventini (2019) also provide vision and examples for how ABMs can be used to build more realistic models of the economy.

In this paper, we discuss the development and adoption of an agent-based model (ABM) called CANVAS at the Bank of Canada, marking one of the inflation-targeting central banks' first ventures of applying a macroeconomic ABM for projection and policy analysis. CANVAS offers an alternative approach by simulating the micro-level behavior of heterogeneous individual agents to provide a comprehensive macro-level view of the economy. This approach has the potential to explain extreme macroeconomic movements observed during events like the financial crisis and the COVID-19 pandemic (Haldane and Turrell, 2018).

This model builds upon the new macroeconomic ABM framework of Poledna et al. (2023), who pioneered the development of a small open economy ABM for Austria. Our work enhances the Austrian ABM in Poledna et al. (2023) and contributes to the macroeconomic agent-based modeling literature in four dimensions. Our first contribution is to provide a comprehensive framework integrating rich household and firm heterogeneity in a production network for the Canadian economy. On the demand side, we model income heterogeneity in the household sector, and persons in the labor force are associated with additional characteristics such as their age, sex, and employed industry. On the supply side, each of the 19 industries is populated by heterogeneous firms that differ in market share, balance sheet conditions, and ownership structures. We use a scale of 1:100 between the model and the data. This level of heterogeneity offers a great advantage since CANVAS is directly linked to Canadian microeconomic data, and model parameters are either pinned down by data or calculated from accounting identities.

Our second contribution is a formal forecasting performance evaluation of the out-of-sample forecasting performance of CANVAS in comparison with standard macroeconomic models such as VAR and a DSGE model. The DSGE model is an estimated large-scale multi-sectoral model that is used for projection and policy analysis at the Bank of Canada. CANVAS shows great strength and outperforms the DSGE model in forecasting GDP growth and key components like consumption. This competitive forecasting performance is encouraging, suggesting that a macroeconomic ABM that encompasses rich household and firm heterogeneity where agents interact in incomplete markets has the potential to enrich macroeconomic policy analysis.

Our third contribution is to improve our understanding of the interplay between expectation formation and cost-push shocks in an inflation-targeting policy regime. We model the adaptive learning behavior of agents by aligning theoretical work on adaptive learning with new survey evidence on Canadian firms' pricing behavior observed through the pandemic (Asghar et al. (2023)). We feature a price-setting rule of firm agents that allows for a decomposition of inflation into three sources: (1) aggregate inflation expectations following adaptive learning; (2) cost-push inflation from higher intermediate production input costs; and (3) demand-pull inflation from increases in demand relative to supply. For an inflation-targeting central bank, the expanded capacity to understand inflation dynamics is of particular benefit.

The last and probably the most important contribution is how we have actively applied a macroeconomic ABM in the monetary policy front line and integrated it as a new model in the central bank's toolkit. Responding to the pandemic challenges experienced by traditional models, CANVAS complements the suite of models used in central banks as an ABM that fits micro and macroeconomic data of the Canadian economy and allows for forecasting of main variables as well as policy analysis through scenarios. In CANVAS, we follow Blattner and Margaritov (2010) to model monetary policy following an augmented Taylor rule specification where both the inflation deviation from the 2 percent target and the GDP growth rate enter the reaction function. We relax the assumption of rational expectations in a flexible inflation-targeting regime with adaptive learning by the central bank agent. This contrasts the design in Poledna et al. (2023) for the Austrian model, where the policy rate is set exogenously by the ECB. By allowing for a meaningful role for the central bank to optimize its policy parameters, the interest rate mimics the role of implementing optimal monetary policy in our model.

Our work is closely related to a strand of literature which supports the application of agent-based models for macroeconomic analysis. CANVAS nests within the family of macroeconomic ABMs discussed by Haldane and Turrell (2018) as complementary to DSGE models. Calibrated based on rich micro- and macro data sets, our model is suited to answer macroeconomic questions where heterogeneity, heuristics, and non-linearities play an important role. CANVAS is one of the first macroeconomic ABMs applied by central banks to support projection and conducting alternative policy scenarios.

CANVAS falls within the classification by Dawid and Delli Gatti (2018) as a large-scale Macroeconomic Agent-Based Model (MABM) since it features more than three agent types—households, firms, and banks—interacting on three markets: consumption goods, labor and credit. Our model design also maps to the three key macroeconomic ABM features. First, time is discrete at a quarterly

[1] Some examples include Freeman (1998), Gintis (2007), Colander et al. (2008), LeBaron and Tesfatsion (2008), Farmer and Foley (2009), Trichet (2010), Stiglitz and Gallegati (2011), Gualdi et al. (2015), Turrell (2016), and Napoletano (2018).

frequency, where goods are traded every quarter, and labor contracts are negotiated on a quarterly basis. Second, decision-making is recursive sequential in our model. For example, each firm decides on the desired level of their production following expectations of GDP growth and inflation and then enters markets one after another to implement those decisions through generating sales. Transactions typically occur at prices which do not clear the market. This may cause a disruption of plans, which must be revised accordingly. Lastly, rather than focusing on a system populated by heterogeneous agents, our model aligns with the approach endorsed by Dosi and Roventini (2019), modeling the macroeconomy as a complex evolving system. Individuals and firms agents are linked by means of employment and trading relationships and have complex interactions through networks. This induces the mechanism for economic shock propagation.

Our emphasis on modeling the production network is inspired by newly emerging literature that added realistic production networks to macro models to better understand how shocks to individual sectors could permeate throughout the economy. For example, Smets et al. (2019) built a multi-sector DSGE model that features an input-output production network and heterogeneous price stickiness of sectors. The authors show that sectoral events and "pipeline pressures" are key sources of volatility in sectoral and headline inflation and a material source of inflation persistence. Similarly, Afrouzi and Bhattarai (2023) found that a network structure featuring strategic complementarity of input-output linkages propagates the impact of a negative productivity shock in upstream firms by increasing the costs and prices of downstream sectors.

Interest in this line of research surged through the pandemic and expanded to macroeconomic agent-based models. Motivated by the impact of supply chain disruptions, Delli Gatti and Grugni (2021) explore the macro-financial consequences of the disruption of a supply chain in an agent-based model through two scenarios over the pandemic. Their framework is characterized by a credit network connecting banks and firms and a production network connecting upstream and downstream firms. Following an economy-wide lockdown, the forced reduction in production of upstream firms generates a large downturn due to the indirect network effects of the shock. The application of our model to analyze the 2019 pandemic experience in Canada also yields comparable insights.

Our detailed calibration to individual and firm heterogeneity is closely related to the HANK literature.[2] Household and firm heterogeneity could amplify the effect of monetary policy on macroeconomic aggregates, as shown in (Kaplan and Violante, 2018; Christiano et al., 2018; Del Negro and Schorfheide, 2013). However, (Fagiolo and Roventini, 2017) argue that HANK DSGE models are restricted to a mild form of heterogeneity. The inherent general equilibrium property in HANK models may imply that the amplification effect of the monetary policy relative to standard DSGE is still somewhat limited. While many simple and easy-to-use time series models like VAR and AR(1) have forecasting power that is as good as or better than the DSGE or HANK alternatives, they have insufficient structure to make them useful for monetary policy purposes. In contrast, ABMs like the one we have developed exhibit a great degree of heterogeneity with assumptions that depart from general equilibrium and rational expectation. Recent work by Poledna et al. (2023) developed the first macroeconomics agent-based model that can compete with and, in the long run, significantly outperform benchmark VAR and DSGE models in out-of-sample forecasting of macro variables. Our paper continues this line of effort by making an additional advancement for central banks to utilize behavioral macro ABMs to produce economic projections and policy analysis.

Our emphasis on modeling the expectation formation process of individuals and firms builds upon a long literature on behavioral adaptive learning. Our choice of modeling the firm's price-quantity setting following a simple heuristic is inspired by findings from Sinitskaya and Tesfatsion (2015). In their work, real-world decision-makers are assumed to be locally constructive in that their decisions are necessarily constrained by their interaction networks, information, beliefs, and physical states. In this setting, the authors found that simpler decision processes (such as simple reactive reinforcement learning) can outperform more sophisticated decision processes, such as adaptive dynamic programming. In a similar spirit, Catullo et al. (2022) have shown that predictive methods, such as machine learning in an agent-based model, are able to formulate expectations (of firm sales) that remain unbiased when shocks are not massive. This simple algorithm provides firms with forecasting capabilities that, to a certain extent, may be consistent with the Lucas Critique. In our ABM, agents learn an optimal AR(1) forecasting rule, learning the correct sample mean and persistence of realized time series.

Lastly, our paper is in line with empirical and lab experimental studies that provide a better understanding of the role of expectations for monetary policy. Learning-to-forecast experiments, as in (Adam, 2007), have been employed to understand how individuals coordinate their forecasts in macroeconomic economies. While forecasts are shown to be largely driven by aggregate expectations, these experiments have demonstrated how the nature of inflation-targeting monetary policies can influence the nature of expectation formation and macroeconomic stability (Pfajfar and Zakelj, 2014; Kryvtsov and Peterson, 2013).

In a more sophisticated expectation modeling framework featuring both rational and non-rational expectations, Assenza et al. (2021) show that heterogeneous expectations tend to self-organize on different forecasting rules depending on monetary policy. Subjects are generally found to form non-rational expectations in that they use historical information rather than relevant current shocks and the data-generating process (including the monetary policy rule) to formulate their forecasts. More aggressive reaction coefficients on inflation and the output gap in the central bank's Taylor rule encourage more stable forecasting behavior and aggregate stability. Macroeconomic experiments have also been used to identify the heuristics individuals and groups use to forecast. Anufriev and Tuinstra (2013) show that the stability of a system depends on the composition of forecasting rules.

Along with the empirical and laboratory evidence, recent advances in ABMs have tried to address the Lucas critique by introducing agents with more sophisticated expectation rules taken from the literature on adaptive learning in macroeconomics (Evans and

[2] A non-exhaustive list of prominent examples of heterogeneous agent New Keynesian (HANK) models includes Kaplan et al. (2018); Kaplan and Violante (2014); McKay and Reis (2016); Khan and Thomas (2008); Chatterjee et al. (2007).

Honkapohja, 2001). The work of Arifovic et al. (2010), Salle (2015), and Dosi et al. (2020) provide new examples of an emerging research stream on learning in agent-based macroeconomic applications.

Our discussion of the model proceeds as follows: Section 2 presents an overview of the basic structure and key characteristics of the model, building on Poledna et al. (2023). The details of the model are described in Appendix A. Section 3 explains the calibration strategy and provides an overview of data used in the model. Section 4 evaluates the out-of-sample prediction performance of CANVAS against different macroeconomic modeling approaches. Section 5 assesses the macroeconomic effects of the COVID-19 pandemic to demonstrate a potential application of our agent-based model, and Section 6 concludes.

2. The model

The key characteristics of our model are as follows. First, our ABM encompasses rich household and firm heterogeneity in one model. For households, we use labor force survey data to model individual income heterogeneity and characteristics such as age, sex, and employment by industry. For firms, we use Canadian business census data to model business demography including market size and financial conditions. Second, interactions between agents take the form of search-and-matching, allowing for trade frictions. We also model the Canadian production network by utilizing input-output tables which contain financial and trade linkages. This allows us to provide a quantitative analysis of the impact of supply chain or labor market shocks on the price-setting decisions of firms. Third, households make investment decisions and firms price-quantity decisions according to a simple heuristic rule of adaptive learning Hommes and Zhu (2014). Furthermore, firms change a product's supply or price based on their perceived local market supply and demand conditions. Fourth, we model the central bank as an agent who can learn the optimal policy parameters associated with an augmented Taylor rule. Lastly, economic growth is driven by agents' expectations as well as their reactions to exogenous shocks and endogenous fluctuations.

Our model is derived from the agent-based model for a small open economy presented in Poledna et al. (2023); however, it features supply, demand, and policy specifications unique to Canada. Furthermore, we also introduce minor differences, such as an inventory accumulation and depletion cycle to reflect firms' motives to avoid stock-out over business cycles, and two exogenous shocks to capture import cost pressure and export price markup fluctuations.

2.1. An overview of the basic structure

The model economy is structured into six sectors: (1) non-financial corporations (firms); (2) households; (3) the general government; and (4) financial corporations (banks), including (5) the central bank. These four sectors interact with (6) the rest of the world (RoW) through imports and exports. Each sector is populated by heterogeneous agents whose balance sheets and economic flows are set according to data from national accounts.

The firm sector is made up of 19 industries (NAICS classification by StatCan), where each industry (firm) produces a perfectly substitutable good using labor, capital, and intermediate inputs with Leontief technology. Firms, subject to fundamental uncertainty, use a simple AR(1) rule to form expectations of the output and (producer price) inflation. Given these, they set prices and quantities. Output is sold to households, to other firms, or is exported. Firm investment is conducted according to the expected wear and tear on capital.

Households earn income and consume in markets characterized by search and matching processes. Employed households supply labor and earn wages; unemployed households receive unemployment benefits; investor households obtain dividend income; and inactive households receive social benefits. Additional social transfers are distributed equally to all households. Similar to firms, households also form AR(1) expectations about the expected growth rate and expected inflation.

The government collects taxes, distributes social as well as other transfers, and engages in government consumption. The banking sector obtains deposits from households as well as from firms and provides loans to firms. Bank profits are calculated as the difference between interest payments received on firm loans and deposit interest paid to holders of bank deposits, as well as write-offs due to credit defaults. (5) The central bank sets the policy rate according to a generalized Taylor rule, provides liquidity to the banking system, and takes deposits from the bank in the form of reserves. Furthermore, the central bank purchases government bonds, acting as a creditor to the government. To model interactions with (6) the rest of the world, a segment of the firm sector is engaged in import–export activities. As we model a small open economy whose limited volume of trade does not affect world prices, we obtain trends of exports and imports from exogenous projections based on national accounts.

Interactions between agents in the model take place on decentralized markets, characterized by search and matching. These interactions are governed by explicit behavioral rules that depict the micro behavior and institutional design of the considered economic system. This search and matching mechanism depends on the probability of a firm being chosen by a customer, which is determined by (1) the offering price of the firm and (2) the size of the firm. The purchased amount then depends on the consumer's consumption budget and the seller's supply. Markets do not necessarily clear; however, the ABM constantly tends towards an approximate equilibrium state and markets, in general, tend to be close to the equilibrium state where demand and supply match.

In our model, there are two variables that agents need to form expectations over: the expected output and producer price inflation. We assume agents form expectations in a homogeneous way: they are boundedly rational and use AR(1) rules to forecast variables in the model economy. This rule is misspecified as it ignores cross-correlations and nonlinearities. However, agents continuously learn and update the parameters of their AR(1) forecasting rule and, in the long run, converge to a so-called misspecification equilibrium where agents have learned an optimal AR(1) rule (a behavioral learning equilibrium (BLE) as introduced by Hommes and Zhu (2014)) and Hommes et al. (2023).

2.2. Firms

There are 19 industries populated with heterogeneous firms in each industry. Each firm produces a principal product using labor, capital, and intermediate inputs from other firms. The firm population of each industry is obtained from business demography data, and the size distribution is chosen to approximately correspond to the firm size distribution in Canada.

We assume each firm is boundedly rational and uses a simple AR(1) rule to forecast output growth and (producer price) inflation. Agents continuously learn and update the mean and persistence parameters of their AR(1) forecasting rule to optimize forecasting performance. Every period, the firm sets both the supply of its product and related price based on its expectation for the aggregate economy, firm-specific cost structure and market demand conditions. We elaborate on these below, and more details about firms' sectors can be found in Appendix A.

2.2.1. Price and quantity setting with simple heuristics

In each period, a firm from an industry produces real output of a principal product with Leontief technology that combines intermediate inputs, labor, and capital. A firm's supply choice depends on its expectations of the aggregate economy and individual supply/demand versus pricing power. It is driven by three sources: (1) its product supply from the previous period; (2) the expected, economy-wide economic growth rate; and (3) the realized, firm-specific growth rate of quantity from the previous period.[3]

Firms set product prices and determine supply based on both aggregate expectations for overall economic conditions as well as firm-specific conditions for cost pressure and market demand. We elaborate on how a firm sets its price and quantity each period using this information.

Aggregate expectations under behavioral learning equilibrium Firms' expectations regarding economic growth and inflation are formed using simple but optimal AR(1) forecasting heuristics.[4]

Agents learn the optimal AR(1) rules with parameters consistent with two observable statistics, the sample mean and the first-order sample autocorrelation (Hommes and Zhu (2014)). Equation (1) summarizes the firm's expectations of the real GDP growth rate ($\gamma^e(t)$) and inflation ($\pi^e(t)$), measured by the log first difference of the GDP deflator:

$$\gamma^e(t) = \mathrm{e}^{\alpha^\gamma(t-1)\gamma(t-1)+\beta^\gamma(t-1)+\epsilon^\gamma(t-1)} - 1 \tag{1a}$$

$$\pi^e(t) = \mathrm{e}^{\alpha^\pi(t-1)\pi(t-1)+\beta^\pi(t-1)+\epsilon^\pi(t-1)} - 1, \tag{1b}$$

where parameters $\alpha^\gamma(t-1)$, $\alpha^\pi(t-1)$, $\beta^\gamma(t-1)$, and $\beta^\pi(t-1)$ are re-estimated every period with the time series of output growth $\gamma(t')$ and inflation $\pi(t')$ where $t' = -T', -T'+1, -T'+2, \ldots, 0, 1, 2, \ldots, t-1$. $\epsilon^\gamma(t-1)$, and $\epsilon^\pi(t-1)$ are random shocks with zero mean and variance re-estimated every period from past observations over the last $T'+t-1$ periods.

In a complex environment of fundamental uncertainty and imperfect information, obtaining accurate forecasts is nearly impossible. Firms in such a complex environment may choose simple forecasting methods that closely monitor the relevant variables, even if such methods fail to understand the complete model of the economy. This approach fits within the concept of procedural rationality (Gigerenzer, 2015). A forecasting method that meets these requirements is the AR(1) forecasting rule: this is a simple procedure for projecting past trends into the future while its forecasting capabilities are relatively high.

Under adaptive learning, the gaps between expected and realized values of state variables will close gradually. This ensures that the unconditional mean and autocorrelations of the unknown non-linear stochastic process—which describe the actual law of motion of the model economy—concur with the unconditional mean and autocorrelations of the AR(1) process in the long run. In fact, adaptive learning with the AR(1) rule leads to convergence to a behavioral learning equilibrium (BLE) in the complex ABM economy, one of the simplest types of misspecification equilibrium put forth in the adaptive learning literature (Hommes and Zhu, 2014).

In our model, consider an example of excess demand when the realized growth rates of a firm have exceeded its growth expectations from the last period. Recognizing its forecasting error from the previous period, it will start increasing production to meet the demand. Production is increased to a point where supply and demand will converge to equilibrium. In contrast, when firms discover they have excess supply where realized growth falls short of expectations, firms will gradually reduce production in order to avoid excessive inventories. Similarly to production quantity adjustment, firms can also adjust their prices to facilitate the convergence to equilibrium.

Should a smaller or larger shock—such as an (endogenous) bankruptcy of a firm or an exogenous demand or supply shock (e.g., the COVID-19 pandemic or an export shock)—pull the economy off the trend, path dependencies might ensue that change the long-term BLE of this model economy. However, after the medium to long turn, adaptive learning will steer the model toward this new BLE, as can be observed in our applications to the economic effects of the lockdown following the COVID-19 pandemic (see Section 5).

Firm-specific cost pressure In addition to setting their expectations of the general economy, each firm also considers how future GDP growth and inflation affect its production costs.

[3] The assumption of Leontief production technology is consistent with the data and is in line with the literature (Assenza et al., 2015a). Moreover, as our explicit aim was to derive the simplest possible ABM that has the features we desire, we relegate all further extensions of the model, such as assumptions on technological progress that change technology coefficients, to further research.

[4] This modeling choice is comparable to other adaptive mechanisms, such as VAR expectations as used in the US Federal Reserve's FRB/US macroeconomic model (Brayton et al., 1997), or expectations according to an exponential moving average (EMA) model, as in Assenza et al. (2015a).

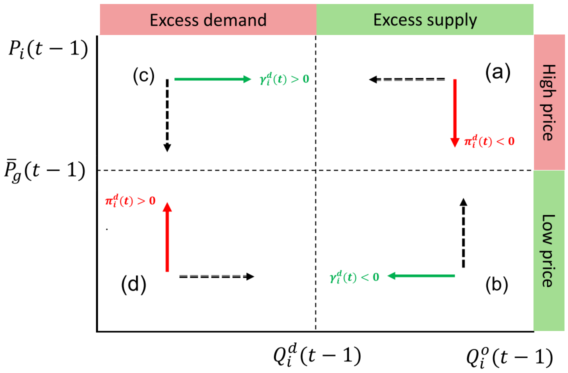

Fig. 1. Firm quantity and price setting.

Each firm uses labor input for production, where employment is measured by the number of persons employed. Demand for labor each period is determined according to the firm's desired scale of activity and its average labor productivity.

Each period, each firm chooses real investment, which adjusts the real capital stock. As in standard DSGE models, capital adjustment in CANVAS is not immediate and is time-consuming. The firms' business investment decision process is modeled by a simple heuristic that accounts for both expectations of the aggregate economy and firm-specific conditions. Each period, firm i observes realized demand and makes a forecast of future demand according to the expected rate of economic growth. Conditional on demand for business investment, the firm's capital stock adjusts accordingly when accounting for depreciation. Under adaptive learning, should realized growth rates surpass growth expectations, investment in subsequent periods will adapt to the approximate trend equilibrium level, and vice versa. As a result, the resulting trend of business investment tends to approximate the trend equilibrium path of this model economy.

Each firm also needs intermediate inputs for production. We assume that each firm holds an inventory stock of each type of input goods. Each period, the firm follows a heuristic of maintaining its inventory stock in positive supply and choosing the desired amount of intermediate goods and raw materials to avoid shortfalls of material input that would impede production. The realized demand for intermediate goods depends on a search-and-matching process. If this firm does not succeed in acquiring the materials it intends to purchase, it will be limited in its production possibilities.

We define the cost-push inflation $\pi_i^c(t)$ as:

$$\pi_i^c(t) = \underbrace{\frac{(1+\tau^{SIF})\bar{w}_i}{\bar{\alpha}_i}\left(\frac{\bar{P}^{HH}(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit labor costs}} + \underbrace{\frac{1}{\beta_i}\left(\frac{\sum_g a_{sg}\bar{P}_g(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit production material costs}} + \underbrace{\frac{\delta_i}{\kappa_i}\left(\frac{\bar{P}^{CF}(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit capital costs}} \quad \forall i \in I_s \tag{2}$$

where, $\bar{\alpha}_i$ indicates the average labor productivity and $\bar{w}_i$ is the average real wage, defined as gross wages, which include both salary costs and employers' contributions to social insurance charged with a rate τ^{SIF}. $\frac{1}{\beta_i}\sum_g a_{sg}$ is real unit expenditures on intermediate production input by industry s on good g, weighted by the average product price index $\bar{P}_g(t)$ (see Equation (49)). δ_i/κ_i are unit capital costs, conditional on the average price of capital goods ($\bar{P}^{CF}(t)$) and capital depreciation relative to productivity growth (where δ_i is the firm-specific capital depreciation rate and κ_i is the productivity coefficient for capital).

Firm-specific demand condition In addition to setting price and quantity based on aggregate expectation and cost pressure from the production network, each firm also chooses to alter its previous period's quantity or price based on its perceived market conditions. We assume that due to asymmetric information and search costs, each firm has a certain degree of pricing power in their local market, so that the law of one price does not apply. We also assume that firms cannot change their quantity and price at the same time.[5]

As a reflection of firms' expectation error concerning demand, "excess supply" is defined as the difference between production and sales. Firms form their expectations of market conditions using two indicators that both rely on observed information from the previous period $t-1$: (1) the level of excess supply, which is the difference between the previous period's supply $Q_i^o(t-1)$ and realized demand $Q_i^d(t-1)$; and (2) the deviation of the firm's price $P_i(t-1)$ from the average price among competitors $\bar{P}_g(t-1)$ for product g. Each firm considers four possible price-quantity setting scenarios (depicted in Fig. 1).

[5] This modeling choice is adapted from Delli Gatti et al. (2011), who use a similar price-quantity heuristic and is motivated by empirical surveys of managers' pricing and quantity decisions; see, e.g., Kawasaki et al. (1982) and Bhaskar et al. (1993). Moreover, there is empirical evidence from laboratory studies showing subjects use similar price-quantity settings heuristics in monopolistic price-quantity settings (see, e.g., Assenza et al. (2015b)).

Effectively, the growth rate of quantity only differs from zero in scenarios (b) and (c):

$$\gamma_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^o(t-1)} - 1 & \text{if } Q_i^o(t-1) \le Q_i^d(t-1) \text{ and } P_i(t-1) \ge \bar{P}_g(t-1) \\ & \text{or if } Q_i^o(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Firm i's supply choice depends on its expectations of the aggregate economy and individual supply/demand versus pricing power. In our model, it is driven by three sources: (1) its product supply from the previous period $Q_i^o(t-1)$; (2) the expected, economy-wide economic growth rate ($\gamma^e(t)$); and (3) the realized, firm-specific growth rate of quantity from the previous period, $\gamma_i^d(t)$:

$$Q_i^s(t) = Q_i^o(t-1)(1+\gamma^e(t))(1+\gamma_i^d(t)). \tag{4}$$

Similar to Equation (3), firms adjust their prices in the following manner:

$$\pi_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^o(t-1)} - 1 & \text{if } Q_i^o(t-1) \le Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ & \text{or if } Q_i^o(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) \ge \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

2.2.2. Inflation determination

With some aggregation and simplification, firm i's nominal price $P_i(t)$ in our model can be decomposed into three components: (1) expectations of economy-wide inflation $\pi^e(t)$ (aggregate inflation expectation); (2) the cost structure of the firm $\pi_i^c(t)$ (cost-push inflation); and (3) the change from the previous period's price $\pi_i^d(t)$ (demand-pull inflation):

$$P_i(t) = P_i(t-1) \cdot \underbrace{(1+\pi_i^d(t))}_{\substack{\text{Demand-pull}\\ \text{inflation}}} \cdot \underbrace{(1+\pi_i^c(t))}_{\substack{\text{Cost-push}\\ \text{inflation}}} \cdot \underbrace{(1+\pi^e(t))}_{\substack{\text{Aggregate}\\ \text{inflation expectation}}} \tag{6}$$

This specification is broadly in line with business survey evidence in Canada found in (Asghar et al., 2023). In usual times, firms' input costs are the key driver of their output prices. When there is broader input cost pressure, the pass-through of input costs to output prices could increase. During these times, inflation expectations could also further influence a firm's price setting.

2.3. Households

The household sector consists of all employed, unemployed, and inactive persons in Canada who are 15 years of age or older, with respective populations obtained from census data and labor force surveys. We model income heterogeneity in the household sector within the labor force. Persons in the labor force (employed and unemployed) are associated with additional characteristics, such as their age, sex, and employed industry. More details can be found in Appendix A.

Labor supply Each person in the labor force either supplies labor to a firm when employed or remains unemployed. If unemployed, the person looks for a job on the labor market from firms with open vacancies in random order and applies for a job through a *search-and-matching* process. Because the worker has occupation-specific skills, job matching occurs when the person accepts a job from the first hiring firm in the same industry as their previous employer. Search-and-matching frictions may occur: a worker remains unemployed if there are no more open vacancies left in the same industry as her former employer. On the other hand, if there are no longer any unemployed in the industry of the searching firm, vacant positions will remain open. For simplicity, we do not consider hiring or firing costs for firms and dismissed employees start searching for new jobs in the same period that they become unemployed.

Consumption Each person purchases consumption goods with a certain budget constraint. Consumers' behavior is assumed to be bounded rational in that they follow a heuristic rule by consuming a fraction of their expected net disposable income. Expected net disposable income is determined according to the household's activity status and the associated labor income stream, expected profits or social benefits and tax payments, the consumer price index of the last period, and expectations of the inflation rate. [6]

We motivate the formulation of the consumption function by the literature of bounded rationality and lab evidence that household consumption behavior follows simple heuristics, as in Delli Gatti et al. (2011). Consumers allocate their consumption budget to purchase different goods from firms.

Similar to how the Consumer Price Index (CPI) is measured in Canada, we assume all households buy the same set of goods, independent of the amount they spend on consumption. The consumption basket includes all goods and services purchased by households in Canada. Each item in the households' consumption basket receives a relative importance, or basket weight, which represents the proportion that households spend on each item. For example, a much larger share of Canadians' spending goes to gasoline than to milk; therefore, gasoline will receive a larger weight than milk in the CPI basket.

[6] As a robustness check, we allowed households to form their expectation of the inflation rate based on CPI inflation instead of GDP deflator inflation, and the differences are negligible.

Once households determine their consumption budget, they visit firms to purchase goods and services according to the search-and-matching mechanism. Whether an individual firm can accommodate consumers' demand depends on its production and inventory stock.

Residential investment The housing market is also modeled by a simple heuristic that each person uses a portion of their income for residential investment. We assume residential investment occurs according to a fixed rate on expected net disposable income. Realized sales of residential investment goods purchased by individuals are an outcome of the search-and-matching process in the housing market.

It is worth mentioning that our modeling choice of residential investment is subject to some limitations. Notably, we don't differentiate borrower households from saver households, therefore abstracting from residential mortgages and related household indebtedness. Given collateralized household debt (that consists of residential mortgages and home equity lines of credit) accounts for more than 80 percent of total household debt in Canada, this simplification will underestimate the role of shock propagation on household consumption. In an extension of this paper, we are leveraging Canadian household microdata (e.g., Survey of Households Spending data (SHS), Survey of Financial Security (SFS), etc.) to introduce a distribution of households in CANVAS to analyze key model properties (including redistributional effects of household heterogeneity in inflation and consumption).

2.4. Other sectors

We provide a brief introduction on fiscal and monetary policies, financial linkages and trade linkages with the rest of the world economy in this section. More details can be found in Appendix A.

2.4.1. Fiscal policy

The government sector is modeled after a large welfare state. A central government collects taxes and social security contributions and distributes social as well as other transfers. Government revenues are composed of taxes on wages (income taxes), capital income (income and capital taxes), firm profit income (corporate taxes), household consumption (value-added tax), other products (sector-specific, paid by industry sectors), firm production (sector-specific), as well as on exports and capital formation, social security contributions by employees and employers, and of other net transfers such as property income, investment grants, operating surplus, as well as proceeds from government sales and services. Government expenditures consist of final government consumption, interest payments on government debt, social benefits other than social benefits in kind, subsidies and other current expenditures. A government deficit adds to the sovereign debt and increases interest payments in subsequent periods.

2.4.2. Monetary policy

The central bank (CB) sets the policy rate $\bar{r}(t)$ based on implicit inflation and growth targets, provides liquidity to the banking system (advances to the bank), and takes deposits from the bank in the form of reserves deposited at the central bank. Furthermore, the central bank purchases external assets (government bonds) and thus acts as a creditor to the government.

The policy rate is determined by an augmented Taylor rule (Taylor, 1993), where the central bank agent learns the optimal parameters. Following Blattner and Margaritov (2010), we include forecasted quarter-over-quarter inflation and real GDP growth in the reaction function:

$$\bar{r}(t) = \rho(t-1)\bar{r}(t-1) + (1-\rho(t-1))(r^*(t-1) + \pi^* + \xi^{\pi}(t-1)(\pi^e(t) - \pi^*) + \xi^{\gamma}(t-1)\gamma^e(t)), \tag{7}$$

where $\rho(t-1)$ is the interest rate smoothing parameter that reflects the gradual adjustment to the policy rate, $r^*(t-1)$ is the real equilibrium interest rate, π^* is the inflation target, $\xi^{\pi}(t-1)$ is the policy parameter on inflation deviations from the target, and $\xi^{\gamma}(t-1)$ is the weight on the forecasted real GDP growth rate. $\rho(t-1)$, $r^*(t-1)$, $\xi^{\pi}(t-1)$, and $\xi^{\gamma}(t-1)$ are re-estimated every period on time series of the real GDP growth rate $\gamma(t')$, inflation $\pi(t')$, and $\bar{r}(t')$ where $t' = -T', -T'+1, -T'+2, \ldots, 0, 1, 2, \ldots, t-1$. As initial conditions for $t' = -T', -T'+1, -T'+2, \ldots, 0$, we use the log differences of real GDP, the GDP deflator (inflation), as well as the Bank of Canada's policy interest rate.

2.4.3. Financial linkages

For reasons of simplicity, we assume that there is one representative financial intermediary for the Canadian economy.[7] The representative bank takes deposits from households and firms, extends loans to firms, and receives advances from (or deposits reserves at) the central bank. The interest rates for loans are set by a fixed markup on the policy rate. Capital of the banking sector grows or shrinks according to bank profits or losses and the write-off of bad debt. The bank is subject to macroprudential policies on both

[7] This assumption of one representative bank is above all due to national accounting conventions. From national annual sector accounts, which determine the logic of financial flows between the aggregate sectors for our model (households, non-financial corporations, financial corporations, government, and the rest of the world), we obtain balance sheet positions (credit and debt) as well as interest payment flows between firms and the financial sector (banks) on an aggregate level. Since we do not have information on financial relations between individual firms (or industry sectors) and banks for this model, we have no empirically based method to determine credit and debt relations, acquisition and provision of credit, as well as interest payments, between individual firms (or industry sectors) and individual banks. Therefore, we account for credit relations and financial flows between individual firms and banks on an aggregate level for the banking sector, i.e., we assume a representative bank extending credit to individual firms according to the amount of firms' real capital stock, while we account for the value added generated by financial corporations in the real economy according to the logic of input-out tables as separate industries within the firm sector.

Table 1
Statistics Canada data tables.

Name	Identifier	CANSIM	Frequency	Start	End
Labor force characteristics by industry, annual	14100023	282-0008	Annual	1/1/76	1/1/21
Canadian Business Counts, with employees	14100304		Semi-annual	7/1/14	7/1/20
Employment by industry, Annual, Canada	14100202	281-0024	Annual	1/1/01	1/1/20
Symmetric input-output tables, summary level	36100084	381-0038	Annual	1/1/13	1/1/19
Flows and stocks of fixed non-residential capital, by sector of industry and type of asset, Canada	36100097	031-0006	Annual	1/1/61	1/1/20
National Balance Sheet Accounts	36100580	378-0121	Quarterly	1/1/90	7/1/21
Current and capital accounts - Households, Canada, quarterly	36100112	380-0072	Quarterly	1/1/61	7/1/21
Current and capital accounts - Corporations, Canada, quarterly	36100116	380-0076	Quarterly	1/1/61	7/1/21
Current and capital accounts - General governments, Canada, quarterly	36100118	380-0079	Quarterly	1/1/61	7/1/21
Canadian Classification of Functions of Government (CCOFOG) by consolidated government component	10100005	385-0041	Annual	1/1/08	1/1/20
Gross domestic product, expenditure-based, Canada, quarterly	36100104	380-0064	Quarterly	1/1/61	7/1/21

Note: The identifier under which the respective data tables are available from Statistics Canada (such as, e.g., 36100104) are shown in the second column. Links to each of the data sources on the Statistics Canada website can be accessed through the series names.

leverage and bank capital. Provision of loans is conditional on a minimum loan-to-value (LTV) ratio, and credit creation is limited by minimum capital requirements.

2.4.4. *Trade linkages*

Foreign linkages of CANVAS are introduced by assuming one representative foreign firm in each sector supplies Canadian imported goods (raw materials, capital, and consumption goods). We also assume homogeneous consumers in the foreign economy who demand Canadian exports. We assume the foreign demand for Canadian exports and the supply of foreign goods to be exogenously given since Canada is a small open economy. Canadian demand for imports is endogenous and is subject to supply constraints.

3. Data & calibration

In this section, we start with a discussion of the calibration procedure from the data sources, followed by the specification of the initial conditions. Following the calibration strategy in Poledna et al. (2023), our model is not calibrated to reproduce so-called stylized facts (moments) of time series but rather to reproduce (and forecast) the time series themselves. For a comprehensive comparison of calibration methods of economic ABMs, see Platt (2020).[8]

The model is calibrated to the Canadian economy for 39 reference quarters from 2010:Q1 to 2019:Q3. Parameters of the model are calibrated so that a period t is one quarter. For each quarter, a wide range of parameters and initial conditions are calibrated to the data so that the model replicates the state of the economy in terms of aggregate GDP, GDP components, and industry sizes.

In general, the calibration procedure involves either taking parameter values directly from the data or calculating them from national accounting identities. For exogenous processes such as imports and exports, parameters are estimated from national accounts. The parameters of the model are summarized in Table 4, where parameter values are shown, as an example, for 2019:Q4.

Data are obtained from Statistics Canada and the Bank of Canada and include *(1) census and business demography*; *(2) labor force survey (3) input-output tables*; *(4) government statistics and sector accounts*; and *(5) national accounts (GDP and main components) and money market interest rates*. Additionally, a number of parameters are calibrated according to *(6) statutory guidelines, financial regulations, and banking practices*.[9] All data sources are reported in Table 1.

3.1. *Firms*

Input-output tables Our model focuses on firms within the 19 industries based on the North American Industry Classification System (NAICS) (see Table 2). The Canadian production network plays a pivotal role in the propagation of shocks in the Canadian economy. In particular, it is crucial to comprehend and capitalize on the intricate connections within the production network to better understand how shocks to individual sectors could permeate throughout the economy. Recent work by Baqaee and Farhi (2021) shows the relationship between production networks and the propagation and amplification of economic shocks, focusing on the COVID-19 pandemic era. They emphasize that the impact of the COVID-19 pandemic on different industries is uneven, and the pandemic acted as both a negative demand shock (reducing household spending) and a negative supply shock (limiting firms' ability to maintain production at pre-pandemic levels). The uneven impact arose from sectoral heterogeneity in labor mobility level since those requiring

[8] Other new calibration methods also feature work by Lamperti et al. (2018) who propose a novel approach of calibrating ABMs by combining machine learning and intelligent iterative sampling. More recently, Shiono (2021) applies a likelihood-free Bayesian inference method called BayesFlow and also showed superior accuracy in estimated ABMs.

[9] Data obtained from Canada's national statistics agency can be found at https://www.statcan.gc.ca/en/start (last accessed March 25, 2022).

Table 2
North American Industry Classification System (NAICS) Canada.

Sector	Code	Short Code
Agriculture, forestry, fishing and hunting	BS110	11
Mining, quarrying, and oil and gas extraction	BS210	21
Utilities	BS220	22
Construction	BS230	23
Manufacturing	BS3A0	31-33
Wholesale trade	BS410	41
Retail trade	BS4A0	44-45
Transportation and warehousing	BS4B0	48-49
Information and cultural industries	BS510	51
Finance, insurance, real estate, rental and leasing and holding companies	BS5B0	52-53
Professional, scientific and technical services	BS540	54
Administrative and support, waste management and remediation services	BS560	56
Educational services	BS610	61
Health care and social assistance	BS620	62
Arts, entertainment and recreation	BS710	71
Accommodation and food services	BS720	72
Other services (except public administration)	BS810	81
Non-profit institutions serving households	NP000	NP000
Government sector	GS600	91

face-to-face contact faced reduced production capacity and employment. Focusing on Canada as a commodity-exporting small open economy, Cao and Dong (2020) examine the importance of production networks where shock to commodity prices yields both aggregate and sectoral GDP impact. From an aggregate perspective, shifts in commodity prices instigate alterations in the value of the domestic currency and inflation rates. Simultaneously, because of strategic complementarity within a production network, fluctuations in commodity prices exert influence on non-commodity sectors through resource reallocation, thereby amplifying the GDP impact.

Based on the detailed input-output table, we provide an illustration of the Canadian production network as in Fig. 2. Focusing on the commodity sector as an example, both energy (plotted in blue) and non-energy (plotted in purple), while being very small (8% and 2% of Canadian GDP), are essential intermediate inputs (for a share of 22%) for production in the manufacturing sector (plotted in green). The manufacturing sector, plotted in green, is of critical importance for the transmission of shocks from commodity sectors. Not only does it account for over 10% of Canada's GDP, but it is also intricately linked to nearly all other segments of the economy, forming a sophisticated network node in the supply chain. Beyond being a key source of GDP and employment, manufacturing sector firms form a complex network with firms within the same sector as well as with firms in other industries (like commodities, constructions, services, etc.). It is not hard to imagine that a negative shock to the commodity sector can propagate through the manufacturing sector, reverberating across the entire economy via the production network. These linkages through the production network are important for understanding industry dynamics.

Initial conditions Initial conditions of the model are set according to the procedure from Poledna et al. (2023) to represent the Canadian economy at each state in time. The distribution of firm sizes in industrial countries is well known to be highly skewed, with large numbers of small firms coexisting with small numbers of large firms (Ijiri and Simon, 1977; Axtell, 2001). Initial employment of firm i ($N_i(0) \quad \forall i \in I_s$) is therefore drawn from a power law distribution with exponent -2 (where $\sum_{i \in I_s} N_i(0) = N_s$ and $N_i(0) > 0$), which approximately corresponds to the firm size distribution in Canada. To determine initial production $Y_i(0)$ of the i-th firm, we use the initial employment by firm $N_i(0)$ and compute the corresponding amount of production by the productivity of labor per unit of output $\bar{\alpha}_i$:

$$Y_i(0) = Q_i^{\mathrm{d}}(0) = \bar{\alpha}_i N_i(0) \ .$$

The initial capital of firm i, $K_i(0)$, (i is part of industry s) is then obtained by dividing firm i's initial level of production $Y_i(0)$ by the productivity of capital κ_i and the desired rate of capacity utilization ω:

$$K_i(0) = \frac{Y_i(0)}{\kappa_i \omega} .$$

Thus, it is the share of the capital of the i-th firm in sector s as measured by production, accounting for the reserve capacity of its capital stock targeted by firm i. The initial stocks of raw materials, consumables, supplies, and spare parts (i.e., intermediate inputs) of the i-th firm ($M_i(0)$) are set such that firms hold sufficient intermediate inputs for expected production without stock-out:

$$M_i(0) = \frac{Y_i(0)}{\omega \beta_i}$$

where $Y_i(0)$ is the initial level of production by firm i, β_i denotes the productivity of intermediate inputs, and $1/\omega$ is the buffer stock of material inputs.

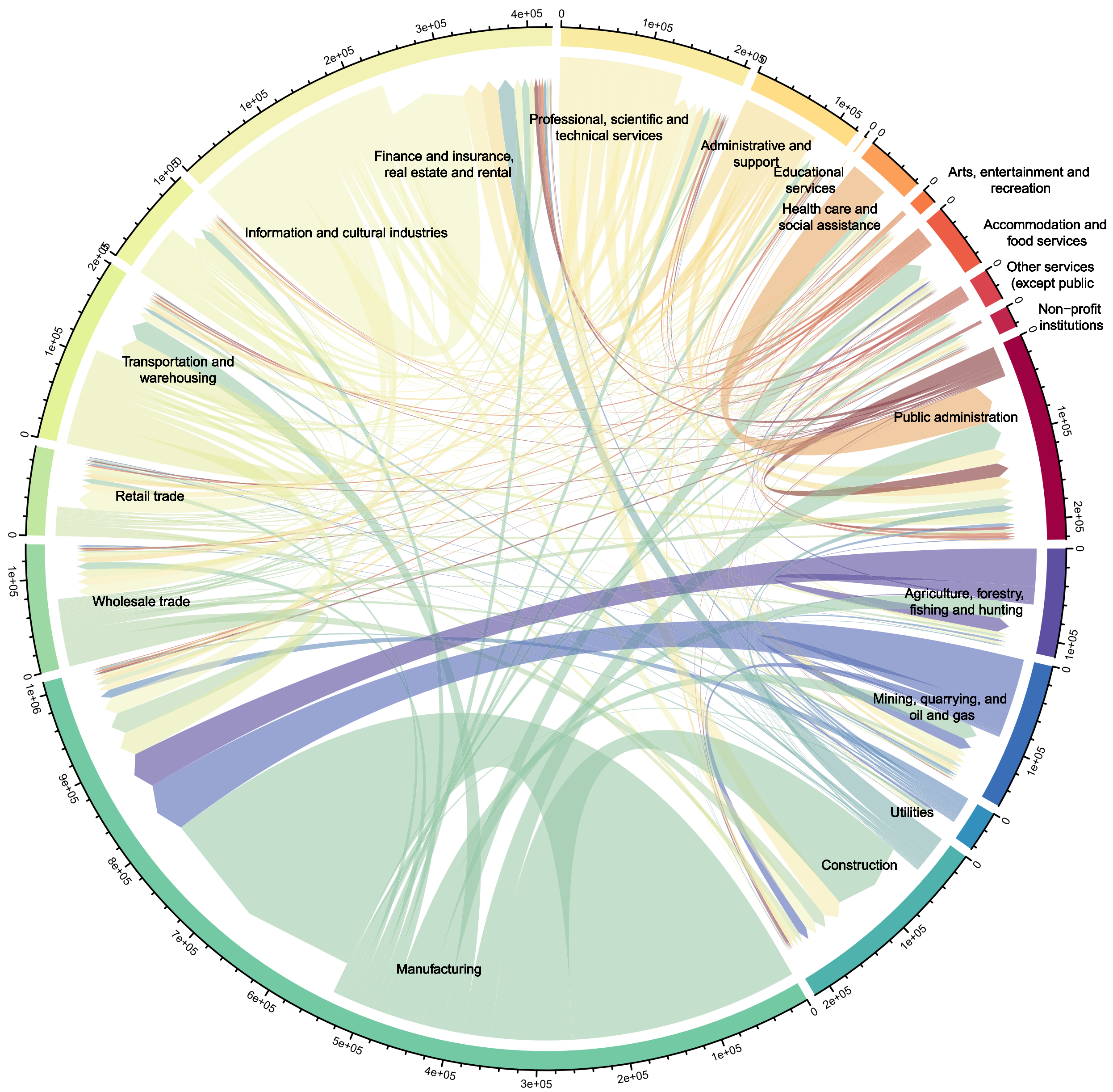

Fig. 2. Canadian production network. Note: The transactions between industries is shown for the sectors: Agriculture, forestry, fishing and hunting [11]; Mining, quarrying, and oil and gas extraction [21]; Utilities [22]; Construction [23]; Manufacturing [31-33]; Wholesale trade [41]; Retail trade [44-45]; Transportation and warehousing [48-49]; Information and cultural industries [51]; Finance and insurance, real estate and rental and leasing [52-53]; Professional, scientific and technical services [54]; Administrative and support, waste management and remediation services [56]; Educational services [61]; Health care and social assistance [62]; Arts, entertainment and recreation [71]; Accommodation and food services [72]; Other services (except public administration) [81]; Non-profit institutions serving households [NP000]; Public administration [91]. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Since a breakdown of financial and current assets for the 19 NAICS sectors is not readily available, we calibrate initial debt $L_i(0)$ to i-th individual firms by disaggregating total firm debts according to the share of the firms' capital stock $K_i(0)$ in the total capital stock $\sum_i K_i(0)$:

$$L_i(0) = L^{\mathrm{I}} \frac{K_i(0)}{\sum_i K_i(0)},$$

where the total amount of firm debt L^{I} is obtained from national balance sheet accounts. The total initial liquidity (deposits) of all firms as an aggregate, D^{I}, is set according to national balance sheet accounts. This aggregate is broken down into single firms by the share of firm i's operating surplus in the overall operating surplus, where we assume that firm liquidity (deposits) moves in line with its production as a liquid form of working capital used for current expenditures:

Table 3
Sectoral parameters.

	I_s	N_s	α_s	β_s	κ_s	δ_s	δ_s^S	w_s	τ_s^Y	τ_s^K	b_g^{CF}	b_g^{CFH}	b_g^{HH}	c_g^G	c_g^E	c_g^I
BS110	496	3586	7.1069	1.6615	0.4337	0.0458	1	0.8043	-0.0026	0.0029	0.0003	0	0.0143	0	0.0341	0.0163
BS210	87	2665	19.8702	2.3689	0.0711	0.0288	1	3.3249	0.0042	0.0141	0.0148	0	0.0023	0	0.1607	0.041
BS220	14	1403	11.2352	3.425	0.0472	0.0223	1	2.812	-0.0165	0.0679	0.0024	0.0001	0.0172	0	0.0041	0.0009
BS230	1499	14694	6.1363	1.8601	2.2919	0.062	1	1.7475	0.0082	0.0371	0.5142	0.8141	0.0004	0	0.0005	0.022
BS3A0	517	17402	11.1372	1.4154	1.3095	0.0622	1	1.939	0.0021	0.0043	0.2612	0.0001	0.1967	0	0.5475	0.729
BS410	574	6270	7.2998	2.674	1.3017	0.0698	1	2.6558	0.006	0.0149	0.0425	0.0003	0.0393	0	0.0474	0.0036
BS4A0	1451	21977	2.0925	2.5929	0.7446	0.0518	1	0.9112	0.0048	0.0177	0	0	0.1194	0	0.0058	0.0119
BS4B0	722	10371	5.0758	1.879	0.2106	0.0313	1	1.4025	-0.0174	0.0142	0.0086	0	0.0359	0	0.0584	0.0231
BS510	186	4061	7.5499	2.0879	0.3898	0.0679	1	1.8432	-0.0037	-0.0044	0.0172	0	0.0361	0	0.0165	0.0162
BS5B0	1001	12028	13.8111	2.9934	1.219	0.0635	1	2.2545	0.0132	0.092	0.0147	0.155	0.3117	0	0.0266	0.0395
BS540	1491	15373	3.447	2.6895	1.7865	0.0975	1	1.3876	-0.0003	0.0041	0.0705	0.0279	0.0068	0	0.0398	0.0286
BS560	544	7681	3.3473	2.582	1.7806	0.065	1	1.3378	0.0062	0.0054	0.0012	0	0.0055	0	0.0126	0.0239
BS610	151	13589	0.1647	2.2701	0.6302	0.0361	1	0.0607	-0.0071	-0.0058	0.0001	0	0.0035	0	0.0001	0.0002
BS620	1220	24962	0.8741	3.6268	1.2125	0.0419	1	0.2956	-0.0101	0.0066	0.0004	0	0.0282	0	0	0.0002
BS710	192	3563	2.0804	1.9501	0.3817	0.0408	1	0.6572	0.005	0.0063	0.0003	0	0.0171	0	0.0047	0.0064
BS720	843	12098	2.2126	1.9607	0.7836	0.0409	1	0.7955	0.0162	0.0119	0.0001	0	0.0678	0	0.0217	0.0293
BS810	1132	8125	1.6944	2.6091	2.3794	0.0669	1	0.7462	0.0038	0.0031	0.0007	0	0.0256	0	0.0004	0.0015
NP000	100	1000	14.2901	2.2927	1.2124	0.0324	1	7.2995	0.021	0.0068	0.0006	0.0002	0.0397	0	0.002	0.0007
GS600	1000	10007	15.0565	2.7331	0.2284	0.0292	1	7.3461	0.0056	0.0108	0.0502	0.0024	0.0326	1	0.0171	0.0056

Note: Sectoral parameters are calculated for 2019:Q4. The contribution of industries is shown for the sectors: Agriculture, forestry, fishing and hunting [BS110]; Mining, quarrying, and oil and gas extraction [BS210]; Utilities [BS220]; Construction [BS230]; Manufacturing [BS3A0]; Wholesale trade [BS410]; Retail trade [BS4A0]; Transportation and warehousing [BS4B0]; Information and cultural industries [BS510]; Finance and insurance, real estate and rental and leasing [BS5B0]; Professional, scientific and technical services [BS540]; Administrative and support, waste management and remediation services [BS560]; Educational services [BS610]; Health care and social assistance [BS620]; Arts, entertainment and recreation [BS710]; Accommodation and food services [BS720]; Other services (except public administration) [BS810]; Non-profit institutions serving households [NP000]; Government sector [GS600]. Parameters are: Number of firms/investors in the s^{th} industry [I_s]; Number of person employed in the s^{th} industry [N_s]; Productivity of labor of the s^{th} industry [α_s]; Productivity of intermediate consumption of the s^{th} industry [β_s]; Productivity of capital of the s^{th} industry [κ_s]; Depreciation rate for capital of the s^{th} industry [δ_s]; Depreciation rate for inventories of thes^{th} industry [δ_s^S]; Wage rate of the s^{th} industry [w_s]; Net tax rate on products of the s^{th} industry [τ_s^Y]; Net tax rate on production of the s^{th} industry [τ_s^K]; Capital formation coefficient of the g^{th} product (firm investment) [b_g^{CF}]; Household investment coefficient of the g^{th} product [b_g^{CFH}]; Consumption coefficient of the g^{th} product of households [b_g^{HH}]; Consumption of the g^{th} product of the government in mln. CAD [c_g^G]; Exports of the g^{th} product in mln. CAD [c_g^E]; Imports of the g^{th} product in mln. CAD [c_g^I].

$$D_i(0) = D^{\mathrm{I}} \frac{\max(\bar{\pi}_i Y_i(0), 0)}{\sum_i \max(\bar{\pi}_i Y_i(0), 0)},$$

where $\bar{\pi}_i = 1 - \left(1 + \tau^{\mathrm{SIF}}\right) \frac{\bar{w}_i}{\bar{\alpha}_i} - \frac{\delta_i}{\kappa_i} - \frac{1}{\beta_i} - \tau_i^{\mathrm{K}} - \tau_i^{\mathrm{Y}}$ is the operating margin. The initial profit of the i-th firm is given by the initial operating surplus and the initial income from interest accrued from deposits less interest payments for bank loans:

$$\Pi_i(0) = \bar{\pi}_i Y_i(0) - r(0) L_i(0) + \bar{r}(0) D_i(0).$$

The initial inventory of finished goods $S_i(t)$ of firm i is assumed to be zero due to a lack of reliable data sources. The initial price of the i-th firm $P_i(0)$ is set to one.

We then derive sector-specific parameters concerning productivity and technology coefficients, as well as capital formation and consumption coefficients from input-output tables in Table 3. The parameters vary by NAICS classification and are calibrated to the annual values for each reference quarter of a calendar year. For parameters that are calibrated based on the data of input-output tables (such as the productivity coefficients for labor and capital ($\bar{\alpha}_i$, κ_i), the depreciation rate (δ_i), and the average wage rate ($\bar{w}_i$)), we use cross-classification tables and structural business statistics (business demography) that link information by industry and product to each sector (see the linkage in Fig. 2).

3.2. Households

Census and business demography data Parameters that specify the number of agents are taken directly from census and business demography data and are scaled appropriately. Several consolidated tables, including input-output tables, demographic data, and cross-classification tables, are compiled for Canada with a breakdown of 19 NAICS activities/products. Parameters concerning the numbers of firms in the s-th industry (I_s) are calibrated to the respective numbers in business demography data. Since business demography data are available annually, we calibrate I_s to the annual values for each reference quarter of a calendar year.

Labor force survey Parameters related to the number of persons in the labor force (employed and unemployed) are obtained from the labor force survey and are scaled appropriately. The calibration of the labor force is aggregated based on the combination of different demographic groups: sex (males and females), age group (young (15–24), prime age (24–54), senior/older (55+)) within each industry. We calibrate H_s^{F15}, H_s^{F25}, H_s^{F55}, H_s^{M15}, H_s^{M25}, and H_s^{M55} to the annual values for each reference quarter of a calendar year.

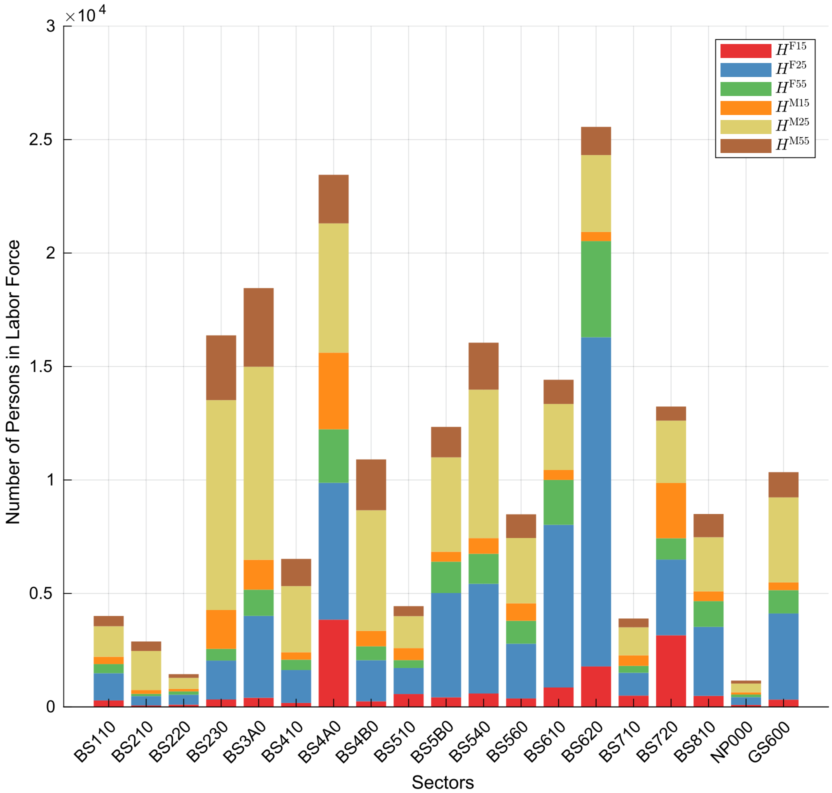

Fig. 3. Number of persons in the labor force (employment and unemployment) in the sectors. Note: Number of employed and unemployed persons (women 15 to 24 years [F15], men 15 to 24 years [M15], women 25 to 54 years [F25], men 25 to 54 years [M25], women over 54 years [F55], men over 54 years [M55]) are shown for 2019:Q4. The contribution of industries is shown for the sectors: Agriculture, forestry, fishing and hunting [BS110]; Mining, quarrying, and oil and gas extraction [BS210]; Utilities [BS220]; Construction [BS230]; Manufacturing [BS3A0]; Wholesale trade [BS410]; Retail trade [BS4A0]; Transportation and warehousing [BS4B0]; Information and cultural industries [BS510]; Finance and insurance, real estate and rental and leasing [BS5B0]; Professional, scientific and technical services [BS540]; Administrative and support, waste management and remediation services [BS560]; Educational services [BS610]; Health care and social assistance [BS620]; Arts, entertainment and recreation [BS710]; Accommodation and food services [BS720]; Other services (except public administration) [BS810]; Non-profit institutions serving households [NP000]; Government sector [GS600].

Initial condition calibration The household sector consists of all employed, unemployed, and inactive persons in Canada who are 15 years of age or older. Persons in the labor force (employed and unemployed) are associated with an age group, sex, and industry as additional characteristics. The respective initial populations are obtained from census data and labor force surveys and are given in Fig. 3 (the number of economically inactive persons is assumed to be constant and given in Table 4). Each household agent (person) is initially assigned to one of the respective cohorts such that the populations are matched. Additionally, each employed person is randomly assigned to a firm that is part of the industry associated with the employee, and investors are assigned to a firm from which they will earn dividends.

The initial wage of the h-th person ($w_h(0)$) is equal to the initial wage paid by firm i ($\bar{w}_i$) if i is the employer of person h; or it is equal to the initial unemployment benefits w^{UB} if the person is unemployed. Initial unemployment benefits are set by dividing the total flow of unemployment payments θ^{UB}, as obtained from government expenditure by function, by the number of unemployed persons. Thus, $w_h(0)$ is determined as follows:

$$w_h(0) = \begin{cases} \bar{w}_i & \text{if employed by firm } i \\ \frac{w^{\mathrm{UB}}}{\theta^{\mathrm{UB}}} & \text{if unemployed.} \end{cases}$$

Initial personal assets (deposits) of the h-th person ($D_h(0)$) are obtained from national balance sheet accounts, which are disaggregated onto the individual level according to the share of each person's income of total income as a proxy for a person's wealth:

$$D_h(0) = D^{\mathrm{H}} \frac{Y_h(0)}{\sum_h Y_h(0)},$$

where D^{H} are the initial personal assets (deposits) of the household sector and $Y_h(0)$ is determined according to Equation (9). The initial capital stock (residential structures such as dwellings) of the h-th person ($K_h(0)$) is obtained from national balance sheet accounts (residential structures of the household sector) and is again disaggregated onto the individual level according to the share of each person's income of total income as a proxy for the person's wealth:

Table 4
An overview of key calibrated parameters.

Parameter	Description	Value	Source
G/S	Number of products/industries	19	census data, labor force survey, business demography data
H_s^{F15}	Number of women 15 to 24 years in the labor force of the s^{th} industry	see Fig. 3	
H_s^{F25}	Number of women 25 to 54 years in the labor force of the s^{th} industry	see Fig. 3	
H_s^{F55}	Number of women over 54 years in the labor force of the s^{th} industry	see Fig. 3	
H_s^{M15}	Number of men 15 to 24 years in the labor force of the s^{th} industry	see Fig. 3	
H_s^{M25}	Number of men 25 to 54 years in the labor force of the s^{th} industry	see Fig. 3	
H_s^{M55}	Number of men over 54 years in the labor force of the s^{th} industry	see Fig. 3	
H^{inact}	Number of economically inactive persons	190855	
J	Number of government entities	3305	
L	Number of foreign consumers	6610	
I_s	Number of firms/investors in the s^{th} industry	see Table 3	
$\bar{\alpha}_i$	Average productivity of labor of the i^{th} firm		input-output tables, flows and stocks capital, national balance sheet; parameters are firm and sector specific
κ_i	Productivity of capital of the i^{th} firm		
β_i	Productivity of intermediate consumption of the i^{th} firm		
δ_i	Depreciation rate for capital of the i^{th} firm		
δ_i^{S}	Depreciation rate for inventories of the i^{th} firm		
$\bar{w}_i$	Average wage rate of firm i		
a_{sg}	Technology coefficient of the g^{th} product in the s^{th} industry		
τ_i^{Y}	Net tax rate on products of the i^{th} firm		
τ_i^{K}	Net tax rate on production of the i^{th} firm		
b_g^{CF}	Capital formation coefficient of the g^{th} product (firm investment)	see Table 3	
b_g^{CFH}	Household investment coefficient of the g^{th} product	see Table 3	
b_g^{HH}	Consumption coefficient of the g^{th} product of households	see Table 3	
c_g^{G}	Consumption of the g^{th} product of the government in mln. CAD	see Table 3	
c_g^{E}	Exports of the g^{th} product in mln. CAD	see Table 3	
c_g^{I}	Imports of the g^{th} product in mln. CAD	see Table 3	
τ^{INC}	Income tax rate	0.1454	government statistics, sector accounts
τ^{FIRM}	Corporate tax rate	0.1551	
τ^{VAT}	Value-added tax rate	0.0902	
τ^{SIF}	Social insurance rate (employers' contributions)	0	
τ^{SIW}	Social insurance rate (employees' contributions)	0.0908	
τ^{EXPORT}	Export tax rate	0.0001	
τ^{CF}	Tax rate on capital formation	0.1338	
τ^{G}	Tax rate on government consumption	0	
r^{G}	Interest rate on government bonds	0.0063	
μ	Risk premium on policy rate	0.0108	
ψ	Fraction of income devoted to consumption	1.0176	
ψ^{H}	Fraction of income devoted to investment in housing	0.1285	
θ^{DIV}	Dividend payout ratio	0.7228	
θ^{UB}	Unemployment benefit replacement rate	0.55	
sb^{inact}	Pension/social benefits in mln. CAD	0.0795	
sb^{other}	Social benefits received by all households in mln. CAD	0.019	
θ	Rate of instalment on debt	0.05	Basel III, BoC statutes, banking practices, literature, etc.
ζ	Banks' capital requirement coefficient	0.03	
ζ^{LTV}	Loan-to-value (LTV) ratio	0.6	
ζ^{b}	Loan-to-capital ratio for new firms after bankruptcy	0.5	
π^*	Inflation target of the monetary authority	0.005	
$\alpha^{\gamma,\mathrm{G}}$	Autoregressive coefficient for government consumption	-0.1376	national accounts (exogenous estimated)
$\beta^{\gamma,\mathrm{G}}$	Scalar constant for government consumption	0.0058	
$\alpha^{\pi,\mathrm{G}}$	Autoregressive coefficient for government prices	0.2659	
$\beta^{\pi,\mathrm{G}}$	Scalar constant for government prices	0.0038	
$\alpha^{\gamma,\mathrm{E}}$	Autoregressive coefficient for exports	0.4016	
$\beta^{\gamma,\mathrm{E}}$	Scalar constant for exports	0.0044	
$\alpha^{\pi,\mathrm{E}}$	Autoregressive coefficient for export prices	0.0292	
$\beta^{\pi,\mathrm{E}}$	Scalar constant for export prices	0.006	
$\alpha^{\gamma,\mathrm{I}}$	Autoregressive coefficient for imports	0.2259	
$\beta^{\gamma,\mathrm{I}}$	Scalar constant for imports	0.0023	
$\alpha^{\pi,\mathrm{I}}$	Autoregressive coefficient for import prices	0.2935	
$\beta^{\pi,\mathrm{I}}$	Scalar constant for import prices	0.0011	
C	Covariance matrix of exogenous variables		

Note: Model parameters are calculated for 2019:Q4. Exogenous autoregressive parameters are estimated starting in 1997:Q1.

$$K_h(0) = K^{\mathrm{H}} \frac{Y_h(0)}{\sum_h Y_h(0)},$$

where K^{H} is the initial lump-sum capital (dwellings) of the household sector.

3.3. Other data sources

In addition to calibrating the model to rich firm- and household-level data, we also include data on government, central bank, international trade and financial systems in our model. For more details on the calibration of the initial conditions in these entities, please see Appendix B.

Government statistics and sector accounts Tax rates and marginal propensities to consume or invest are calculated from national accounting identities. These rates are set such that the financial flows observed in input-output tables, government statistics, and sector accounts are matched. Capital ratios and the inflation target of the monetary authority are set according to the literature. In the context of the model, we define an average tax rate as the aggregate tax flow paid by an institutional sector (firms, households, etc.) in a calendar year divided by the corresponding aggregate monetary flow that serves as the base for the tax and that is received by the same institutional sector (such as income, profit, output, fixed assets, etc.). This annual average tax rate obtained from macroeconomic aggregates is then applied to every individual agent in our model in the corresponding economic context. We thus calibrate tax rates and marginal propensities to consume or invest to the annual values for each reference quarter of a calendar year. Households' marginal propensity to consume (ψ) and invest (ψ^{H}) are calibrated such that consumption out of disposable income equals actual household consumption, and investment in dwellings is as obtained from input-output tables for Canada.

Exogenously estimated from national accounts (GDP and main components) For exogenous processes such as imports and exports, parameters are estimated from national accounts. The growth rates of real imports, real exports, and the final government expenditure of the general government, as well as the respective deflators, are assumed to follow AR(1) processes. The coefficients of the respective AR(1) models are estimated over the sample from 1997:Q4 to the respective reference quarter of the calibration. The sample 1997:Q1 to 1997:Q3 is used as a pre-sample period.

Statutory guidelines, financial regulation, and banking practices A number of parameters are calibrated according to statutory guidelines, financial regulation (Basel III), and banking practices. Since the statutory guidelines and regulations did not change during the calibration period, these parameters are assumed to be constant for all reference quarters. The capital ratio (ζ) and the inflation target of the monetary authority (π^*) are set according to financial regulation (Basel III) and the statutes of the Bank of Canada (2 percent inflation target). We calibrate the unemployment benefit replacement rate (θ^{UB}) with the data of the basic rate of the Employment Insurance (EI) program, at a level of 55%.

4. Forecasting performance

We conduct a series of forecasting exercises to evaluate the out-of-sample forecasting performance of CANVAS in comparison with standard macroeconomic modeling approaches. The out-of-sample forecasting exercise is constructed along the lines of Smets and Wouters (2007), who compare a Bayesian DSGE model to an unconstrained VAR as well as to Bayesian VAR (BVAR) models.[10]

We compare the out-of-sample forecast performance of CANVAS to that of an unconstrained (non-theoretical) VAR(1) model,[11] the Bank of Canada's main DSGE model (ToTEM), and an AR(1) model. We do this by means of the root mean squared forecast error (RMSE).[12] To test whether the models' forecasts are significantly different from that of the VAR(1) forecasts, we conduct Diebold-Mariano tests correcting for the overall length of the forecasting horizon (Harvey et al., 1997). In this test, the null hypothesis is that each model and the VAR(1) generate forecasts of equal accuracy.

VAR We use the VAR model as the benchmark for the forecast performance comparison as the VAR is guaranteed to summarize the data in-sample. A drawback, however, is that even very small VAR models have a large number of parameters, whose estimates tend to be imprecise when estimated with short samples.

The benchmark VAR is estimated by including the log differences of real GDP, real household consumption, real capital fixed investment, real exports and real imports of Canada, as well as the log difference of the GDP deflator (a focused measure of inflation) and the Canadian Overnight Repo Rate Average. The VAR is initially estimated over the sample 1997:Q1 to 2010:Q1 and used to produce 12-quarters-ahead out-of-sample forecasts using 2010:Q1 as the last observation. The VAR is then re-estimated recursively

10 Following Smets and Wouters (2007), and for reasons of data availability, we are restricted to using the latest vintage of data available from Statistics Canada at the time of model estimation. Since in this study, as in Smets and Wouters (2007), we are primarily interested in how well CANVAS fits the data of the Canadian economy, and not in benchmarking its forecasting performance with potentially inconsistent real-time data, conducting a real-time forecast evaluation along the lines of, e.g., Diebold et al. (2017) is left to future research.

11 To determine the optimal lag length of the VAR model, the Bayesian information criterion (BIC) is minimized. For the entire period from 2010:Q1 to 2019:Q4, VAR models of lag order one minimize the BIC.

12 The root mean squared error is defined as follows: $RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{T}(\hat{x}_t - x_t)^2}$, where $\hat{x}_t$ is the forecast value and x_t is the observed data point for period t.

Table 5
Out-of-sample forecast performance.

	GDP	Inflation	Consumption	Investment	Exports	Imports
VAR(1)	*RMSE-statistic for different forecast horizons*					
1q	0.48	0.73	0.33	1.54	2.17	1.8
2q	0.76	0.68	0.54	2.7	2.98	2.68
4q	1.24	0.65	1.01	5.19	3.53	4.55
8q	1.9	0.69	1.66	9.95	4.57	9.22
12q	2.24	0.71	1.98	15.14	4.65	13.83
AR(1)	*Percentage gains (+) or losses (-) relative to VAR(1) model*					
1q	-0.4 (0.94)	10.4 (0.06*)	13.1 (0.15)	5.8 (0.52)	-2.2 (0.67)	14.9 (0.14)
2q	1.7 (0.77)	2.6 (0.35)	4.9 (0.46)	11.4 (0.19)	5.7 (0.39)	23.2 (0.03**)
4q	11.1 (0.00***)	-0.5 (0.85)	6.4 (0.33)	17.3 (0.11)	2.5 (0.45)	44.3 (0.01***)
8q	10.6 (0.00***)	3.3 (0.34)	7.7 (0.55)	21.2 (0.04**)	-5.7 (0.50)	60.4 (0.01***)
12q	18.6 (0.07*)	2.8 (0.26)	8.7 (0.72)	26 (0.00***)	-16.4 (0.38)	68.6 (0.06*)
ToTEM	*Percentage gains (+) or losses (-) relative to VAR(1) model*					
1q	-27.2 (0.09*)	14.4 (0.07*)	-49.2 (0.00***)	-18.8 (0.03**)	14.9 (0.05**)	24.2 (0.00***)
2q	-56 (0.01***)	7.3 (0.09*)	-77.5 (0.00***)	-28.7 (0.02**)	20.4 (0.16)	27.6 (0.01***)
4q	-73.4 (0.00***)	1.9 (0.71)	-76.7 (0.02**)	-16.8 (0.15)	6.8 (0.67)	30.1 (0.02**)
8q	-58.5 (0.03**)	8 (0.14)	-56.6 (0.18)	15.9 (0.50)	8.7 (0.78)	48 (0.00***)
12q	-33.8 (0.29)	6.4 (0.23)	-39.2 (0.07*)	41.5 (0.01***)	24.7 (0.19)	64.9 (0.03**)
CANVAS	*Percentage gains (+) or losses (-) relative to VAR(1) model*					
1q	-0.1 (0.99)	10.2 (0.08*)	-49.1 (0.01***)	5.4 (0.50)	0.7 (0.90)	14.2 (0.17)
2q	2.4 (0.66)	-1.2 (0.68)	-64.8 (0.03**)	13 (0.01***)	3 (0.67)	23.9 (0.05**)
4q	14.8 (0.02**)	-4.5 (0.22)	-20.5 (0.53)	23.4 (0.08*)	-6.3 (0.35)	41.8 (0.03**)
8q	18.4 (0.04**)	-9.7 (0.07*)	11.7 (0.76)	33.7 (0.08*)	-17.6 (0.19)	65 (0.01***)
12q	33.6 (0.00***)	-1.8 (0.55)	34.5 (0.64)	43.3 (0.00***)	-38.5 (0.03**)	80.6 (0.05**)

Note: The forecast period is 2010:Q2 to 2019:Q4. All models are re-estimated each quarter and the results are obtained as an average of 500 Monte Carlo simulations. In parentheses, we show *p*-values of (modified) Diebold-Mariano tests (Harvey et al., 1997), where we test whether forecasts are significantly different from the VAR(1) (the null hypothesis of the test is that CANVAS, AR(1), and ToTEM are less accurate than the VAR(1)). *, **, and *** denote significance at the 10 percent, 5 percent, and 1 percent level, respectively.

for each quarter by extending the last observation from 2010:Q2 to 2019:Q3. For each observation between 2010:Q1 and 2019:Q3, a set of 12-quarters-ahead out-of-sample forecasts are produced. The average RMSEs of these forecasts by horizon are reported in Table 5.

AR We also compare the ABM's forecasting performance to more tightly parameterized univariate AR models. As in the VAR model, we use a similar methodology to determine the optimal lag length for the AR models. For the entire period from 2010:Q1 to 2019:Q3 and for all variables, AR models of lag order one minimize both the AIC and BIC.

DSGE We conduct a similar out-of-sample forecasting exercise in ToTEM. ToTEM is a large-scale, open-economy, dynamic stochastic general equilibrium (DSGE) model that is built around the New Keynesian paradigm (Murchison and Rennison, 2006). Since ToTEM features an enriched firm- and individual-level heterogeneity, it serves as a relevant DSGE candidate to assess the relative performance of CANVAS. To help interpret the forecasting performance results, we provide a brief introduction of ToTEM's modeling structure. For more details on ToTEM, see Corrigan et al. (2021).

On the firm side, the model features five distinct sectors producing final goods for consumption, residential investment, business investment, government spending, and non-commodity exports. The model also includes a separate commodity-producing sector. The firms responsible for producing final goods face nominal rigidities when setting their prices. The model features three prominent household types differing in the financial markets they have access to and in their status as savers or borrowers in those markets. Analogously to the VAR, ToTEM is initially estimated over the sample 1997:Q1 to 2010:Q1 to produce 12-quarters-ahead out-of-sample forecasts and is then re-estimated recursively for each quarter by extending the last observation from 2010:Q2 to 2019:Q3.

CANVAS Similar to the VAR, AR, and DSGE models, CANVAS is calibrated 39 times to different reference quarters over the calibration period from 2010:Q1 to 2019:Q3. Once the model is calibrated to a reference quarter, it reproduces exactly the state of the economy in that quarter in terms of aggregate GDP, GDP components, and industry sizes. Starting from each reference quarter, the model is run for 12 quarters, allowing it to collect model-based out-of-sample forecasts. The average of 500 Monte Carlo simulations is used as our point estimate for evaluating the forecasting accuracy.

Table 5 shows the percentage difference between the RMSE of the benchmark VAR(1) and each of the three models (i.e., AR(1), ToTEM, and CANVAS). A positive sign means that the model has a lower RMSE than that of VAR(1), suggesting superior forecasting ability in the model. In parentheses, the *p*-value of the Diebold-Mariano test is used to test if the difference in forecasting performance is statistically significant.

ToTEM has better but not statistically different forecast performance compared to all other models in forecasting inflation and exports for all horizons. The only exceptions are the one-quarter-ahead forecast for exports and the two-quarter-ahead forecast for inflation, where its forecasting gains compared to all other models are significantly higher. The strength of ToTEM in forecasting inflation likely benefits from its enriched multi-stage production network with both nominal and real rigidities. In contrast, ToTEM fails to improve on VAR(1) and AR(1) at forecasting GDP and consumption and only improves on the VAR(1) forecasts for investment at the longer horizons.

Both ToTEM and CANVAS forecast imports relatively well, improving upon the VAR(1) model. Moreover, both models generally perform better than VAR(1) and AR(1) at longer horizons, with a few exceptions. It is worth highlighting that CANVAS yielded the lowest RMSEs in predicting GDP and investment among all the models and improves upon ToTEM's consumption forecasts, especially at the 8q- and 12q-ahead horizons.

Both CANVAS and ToTEM generally exhibit difficulties in explaining household consumption in Canada in the short run (i.e., over one year). Beyond one year, CANVAS shows great strength and outperforms ToTEM in forecasting consumption. This competitive forecasting performance relative to ToTEM is impressive, suggesting that incomplete markets, non-linear behavior of households in consumer goods, etc., are somewhat better encompassed in the behavioral model.

5. Application: understanding pandemic's impact in Canada

To gain some insights into the economic effects of the recent COVID-19 pandemic in Canada, we apply CANVAS to model the evolution of the Canadian economy since 2020:Q1. Apart from the direct personal and social costs, the pandemic had far-reaching economic consequences, from supply-side manufacturing issues to decreased consumer activity due to lockdown measures, as well as higher unemployment and rising debt levels. To limit the impact of the pandemic, the Canadian economy has been supported by a range of extraordinary measures. Monetary policy has deployed a variety of targeted programs to ensure the proper functioning of credit and financial markets. In March 2020, the policy rate was lowered to its ELB. Fiscal policy has provided liquidity to households and businesses to prevent inefficient defaults and bankruptcies. In the April 2020 Monetary Policy Report, a summary of actions taken by the monetary and fiscal authorities was provided as a response to COVID-19.[13]

Our analysis demonstrates how CANVAS can provide insights into the likely trajectories of an open economy when confronted with a variety of shocks. The level of detail of our model allows for the measurement of economic reactions to the COVID-related lockdown measures within particular industries and specific populations, as well as the tracking of the propagation of these measures through the economy. We focus on three aspects: (1) stages of the pandemic, (2) sector heterogeneity, and (3) labor market heterogeneity.

5.1. Scenario design

To isolate the economic effects at different stages of the pandemic, we investigate three scenarios: the "Baseline," the "Lockdown," and the "Lockdown and supply chain crisis."

Baseline The "Baseline" scenario shows the macroeconomic dynamics without the pandemic. Conditional on the state of the economy in 2019:Q4, we use the model to conduct eight-quarters-ahead out-of-sample projections until Q4:2021. Represented by the green line in Figs. 4 and 5, the mean model projections under this scenario are shown. In the baseline scenario (i.e., in the absence of the pandemic), Canadian GDP would have been on a steady growth path, with annual inflation remaining close to 2% (Fig. 5).

Lockdown Following the initial shutdown that lasted until mid-May 2020, the Canadian economy suffered from a sharp contraction (see solid line showing "data" in Fig. 4, upper right panel). This sharp contraction is reflected in the "Lockdown" scenario (the blue line in Figs. 4 and 5). This includes the impact of lockdown measures in Canada and the rest of the world, which is modeled through a supply shock that exogenously reduces firms' supply in 2020:Q1 and 2020:Q2. In particular, this is implemented through a production contraction in domestic firms and a trade adjustment of foreign firms. To capture heterogeneous changes in production in different industries, industry-level GDP data from 2020:Q1 and 2020:Q2 is fed into the model. Realized import and export data, from the same quarters, account for the impact of foreign lockdowns. All other components from the baseline scenario remain the same. The result of this specification is that the economy experiences a large, initial negative shock but rapidly rebounds to a new growth path similar to the one under the baseline scenario (Fig. 4). With regards to inflation (Fig. 5), there is increased volatility in both measures. However, over the long term, annualized inflation rates remain close to the baseline forecasts.

Lockdown and supply chain crisis The third scenario is labeled "Lockdown and supply chain crisis," represented by the red line in Figs. 4 and 5. This scenario accounts for the development of global commodity prices since 2021 by adding observed imports and exports up to 2021Q4. All other components are identical to the lockdown scenario. This added export and import data affect the model in two ways: exports account for the impact of foreign (and thus aggregate) demand on the Canadian economy, while prices of imports reflect firms' production costs (since imports largely include intermediate outputs used in domestic goods production). Domestic prices of all sectors are determined endogenously, and export and import price deflators are exogenous in this application. Under this scenario, the Canadian economic recovery is slower to materialize, and the long-run GDP is lower than in the first two scenarios. Inflation is similar to the outcome under the lockdown scenario, if not slightly more volatile at longer horizons.

[13] See Table 1 "Summary of Key Policy Measures," https://www.bankofcanada.ca/wp-content/uploads/2020/04/mpr-2020-04-15.pdf.

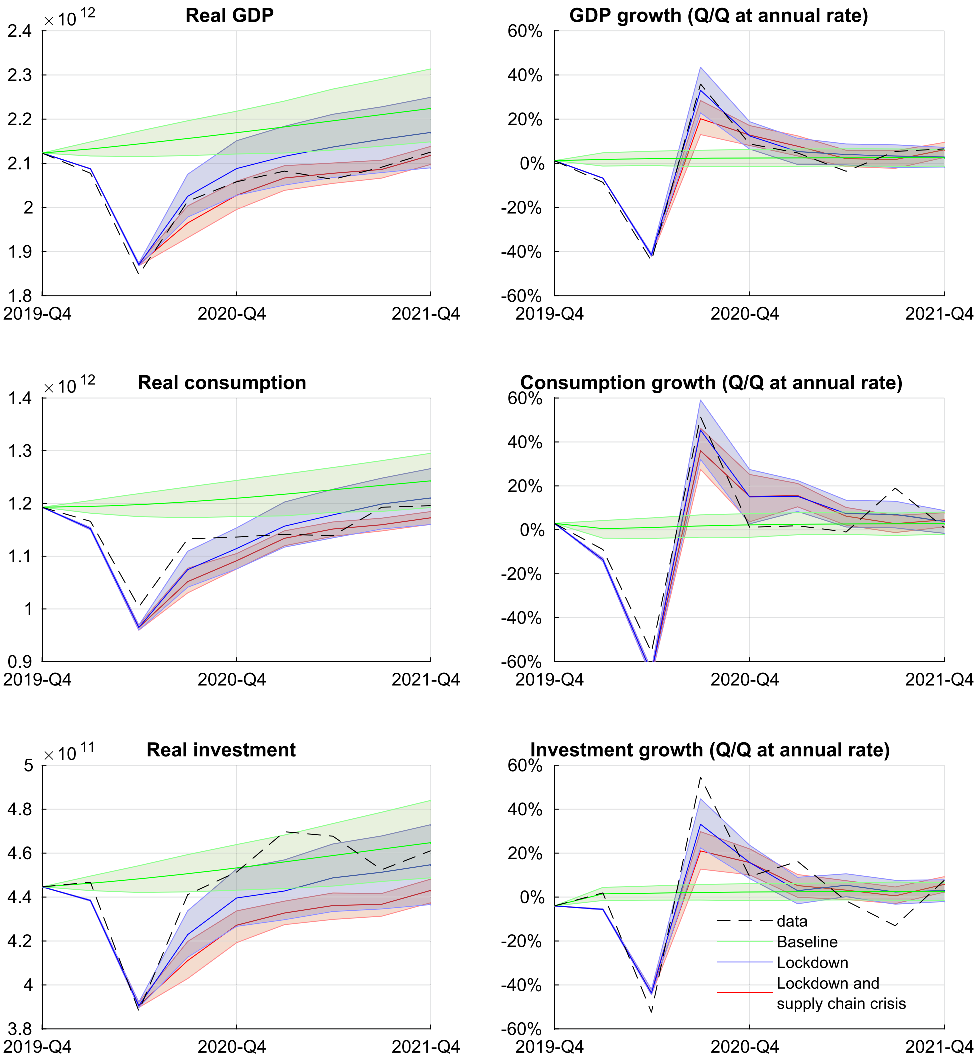

Fig. 4. GDP and selected components. Note: Impact of economic scenarios on quarterly macroeconomic variables with respect to the baseline scenario. One standard deviation is plotted around the mean trajectory. Model results are obtained as an average of 500 Monte Carlo simulations. The left panel shows quarterly levels, whereas the right panel shows quarterly growth at annualized rates.

In Canada, the inflation targeting framework is established around total CPI inflation. CPI is a measure of goods purchased by consumers. Since we don't model CPI directly in the model, we report two alternative measures of inflation rates from model simulations: (1) consumption deflator inflation and (2) GDP deflator inflation, as seen in Fig. 5. As in Amiti et al. (2019), we use producer price indexes instead of consumer price indexes because a clear mapping between international products and domestic industry categories is only available for producer price categories. The producer price indexes, therefore, more effectively measure the price received by domestic firms for their goods or services, consisting of both intermediate and final goods.

Comparing between scenarios, Fig. 5 shows that the lockdown scenario is able to explain the initial increase of GDP deflator inflation relative to the baseline scenario in 2020 (lower right panel). However, after an initial spike, inflation returns relatively close to the target under this scenario. In contrast, the model most closely tracks inflation and GDP components in the "Lockdown and supply chain crisis" scenario when international commodity prices are considered (Figs. 4 and 5). In particular, GDP deflator inflation experiences fluctuations into 2021, rising to a high of around 10 percent in 2021Q2. This suggests that post-pandemic inflation can be traced back to two main causes. The first cause is domestic and is related to the rapid increase in demand following the lifting of lockdown restrictions. Firms react to the demand shock by increasing prices. The second cause is the international increase in commodity prices observed in 2021, which raises firms' intermediate costs and is then translated into their prices.

5.2. Uneven impact of the lockdown across sectors

CANVAS allows further complementary macroeconomic analysis with its ability to track dynamics at the firm and industry levels.

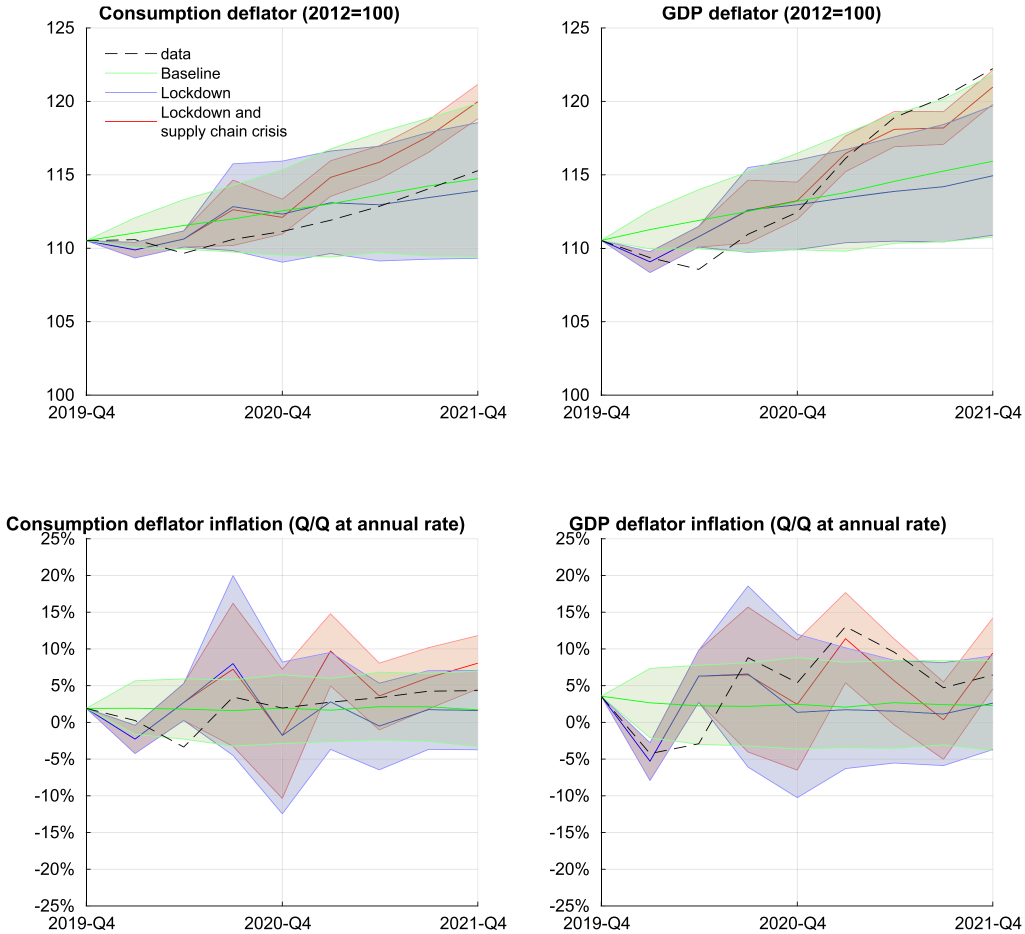

Fig. 5. Inflation. Note: Impact of economic scenarios on quarterly inflation measures with respect to the baseline scenario. One standard deviation is plotted around the mean trajectory. Model results are obtained as an average of 500 Monte Carlo simulations. The top panel shows quarterly GDP deflator and consumption deflator levels, whereas the bottom panel shows quarterly GDP deflator inflation and consumption deflator inflation, both at annualized rates.

Sectoral inflation Fig. 6 decomposes the role of individual industries in creating inflation in each of the scenarios. Manufacturing is shown to be the main industry contributing to inflation in Q3:2020. In contrast, service sectors play a more prominent role in Q1:2021. Commodity sectors caused, to a large extent, deflation in Q1 and Q2:2020 and were one of the main contributors to inflation from 2020:Q4 onward.

The energy commodity sector, including mining, quarrying, and oil and gas extraction, is a key sector of the Canadian economy. As the world's fourth largest oil producer in 2018, investment in the oil and gas sector accounts for about 30 percent of total business investment. Canada is also a net oil exporter, with about 75 percent of commodity production being exported. As a result, the sharp energy price increase had a significant impact on the Canadian economy through several channels and had important implications for household expenditures and balance sheets. In addition to the impact through terms of trade, crude oil also directly accounts for the largest weight in the Bank of Canada Commodity Price Index (BCPI), given its large share (about 45 percent) of the value of Canada's commodity production. With calibration and estimation, CANVAS is uniquely positioned to help us better understand the implications of the oil price movement and its impact on Canada.

Scetoral GDP growth Similarly, sectoral GDP also experiences large variations as the pandemic evolves. The sectoral decomposition of GDP dynamics in Fig. 7 shows that hard-to-distance sectors (including construction, wholesale and retail trade, transportation, accommodation and food services, as well as arts, entertainment, recreation, and other activities) experience a much steeper decrease in output due to the shutdown.

The accommodation and food services sector, for instance, experienced a decline of 50 percent at a quarterly rate during the initial lockdown in 2020:Q1 and Q2 and a rapid recovery in 2021. The decline in output is only partially compensated for by the subsequent expansion in the three-year simulation period, so that sectoral output, especially for transportation, accommodation and food services, as well as arts, entertainment, recreation, and other activities, remains below the pre-pandemic output until the end of 2021. Apart from these sectors, most industries have returned close to the baseline growth path. This reflects solid fundamentals,

Fig. 6. Decomposition of GDP deflator inflation by industry (%, Q/Q at annual rate). Note: Decomposition of GDP deflator inflation by industry is shown for the "Lockdown and supply chain crisis" scenario.

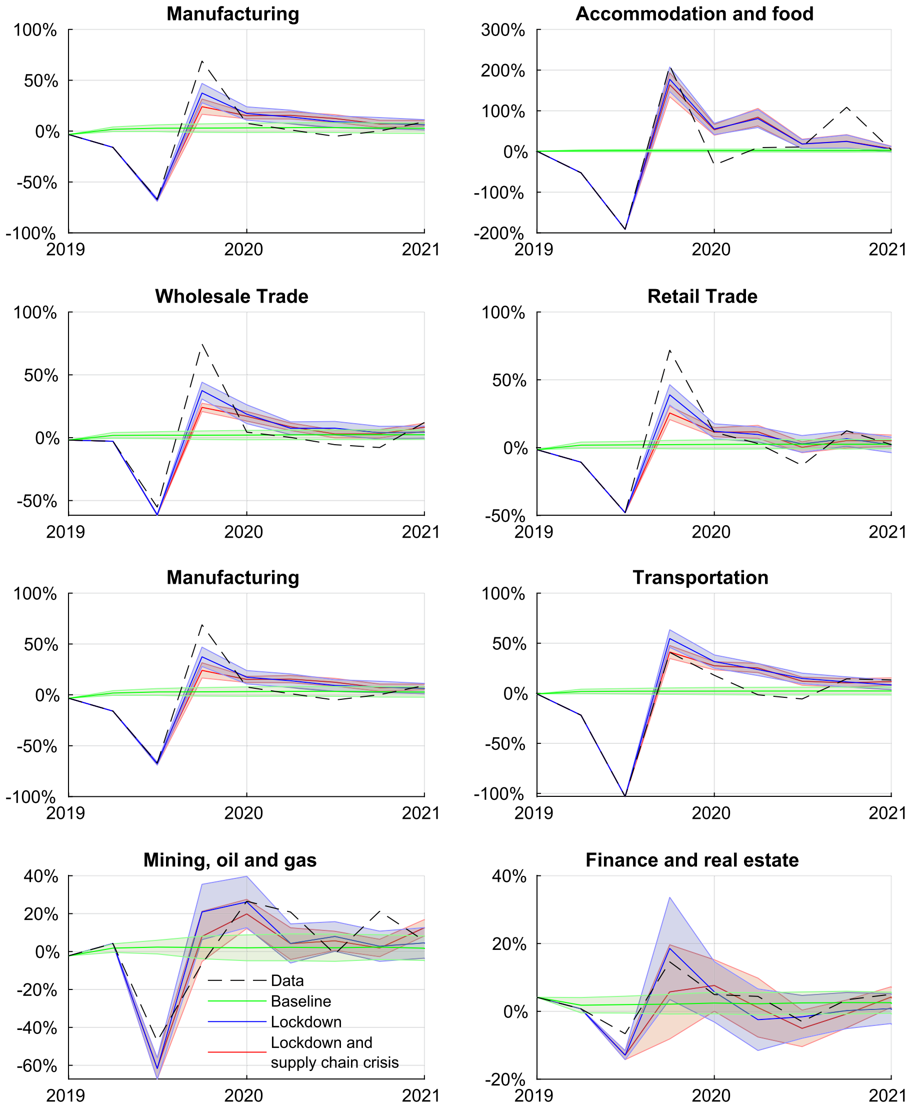

Fig. 7. GDP growth by industry (Q/Q at annual rate, %).

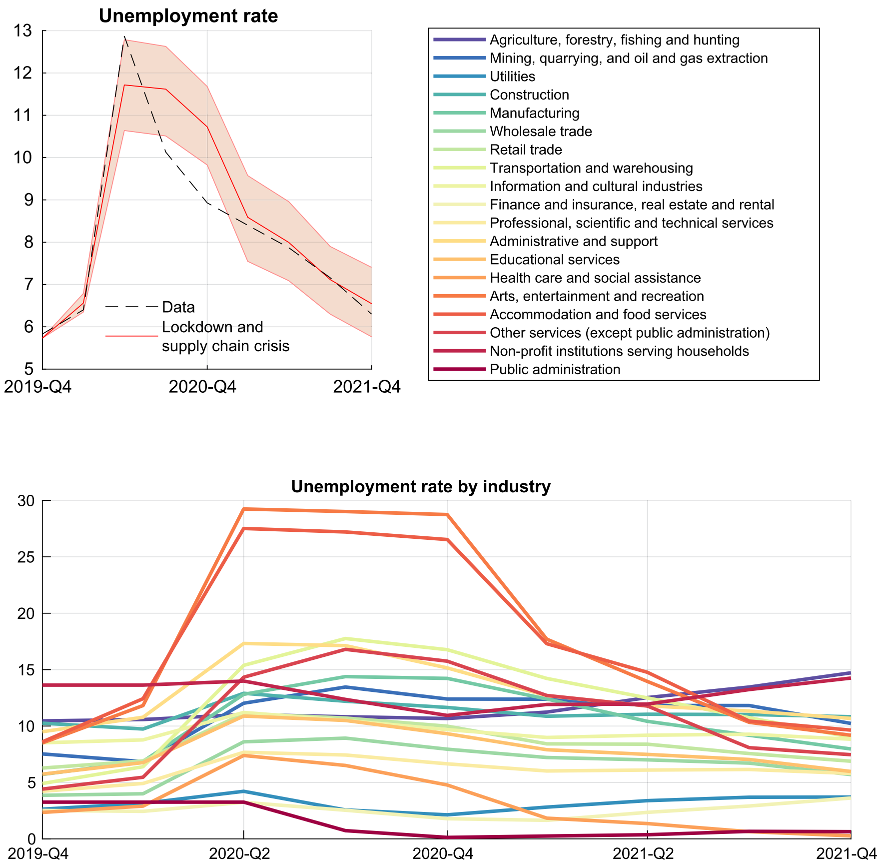

Fig. 8. Unemployment rate: aggregate vs sectoral (%). Note: Simulated dynamics of the unemployment rate at the aggregate level and by industry are shown for the "Lockdown and supply chain crisis" scenario.

notably that the recovery in the labor market, fiscal support, and favorable terms of trade are supporting the level of disposable income and household consumption over the near-term simulations.

Investigating more closely the hardest-hit sectors during the pandemic, we observe that some played a larger role than others in Canada's economic performance. For example, while the manufacturing sector is relatively small, making up 10% of the economy, it is important because it drives activity in other sectors. The sector itself is diverse, including food, machinery, transportation equipment, chemical products, and several others. During the containment, the manufacturing sector experienced a very sharp decline (of about 17 percent), and its sectoral growth remained below the level of other service sectors through 2020:Q3. In contrast, the high-contact sector of accommodation, food, and recreation experienced a very large initial contraction. However, since its share of Canadian GDP is only 3 percent, its overall impact on GDP is insignificant.

5.3. Labor market impact at granular level

Our ABM can also shed some light on labor market developments. In April 2020, the Canadian government rolled out the Canada Emergency Wage Subsidy (CEWS) to qualifying employers (of all sizes and across all sectors) whose revenues were impacted by COVID-19. CEWS was intended to provide an incentive for employers to pay their employees who were sent home due to lack of work or for health and safety reasons. This, in turn, prevented further job losses and enabled employers to rehire employees who had been laid off. Even though a significant proportion of Canadian companies have received fiscal support to avoid laying off their workers, the effects of the pandemic on labor markets are still tremendous.

The simulated unemployment rate in our model with CEWS rises to about 13 percent in 2020 (see Fig. 8). It is particularly compelling to note that the labor market takes a longer time to recover than GDP: unemployment does not return to levels seen before the COVID-19 crisis until the end of the simulation period (winter 2021). As in other countries around the globe, massive amounts of additional government funding were required to support companies and households and keep the Canadian economy afloat.

Our findings can be related to the Bank of Canada's significant ongoing efforts to understand the labor market implications of the pandemic. Ens et al. (2021) provide a new, detailed approach to identify important areas of weakness (or strength) in the labor market. They construct the expanded labor market indicator (ELMI) by featuring changes in methodology and an expanded scope

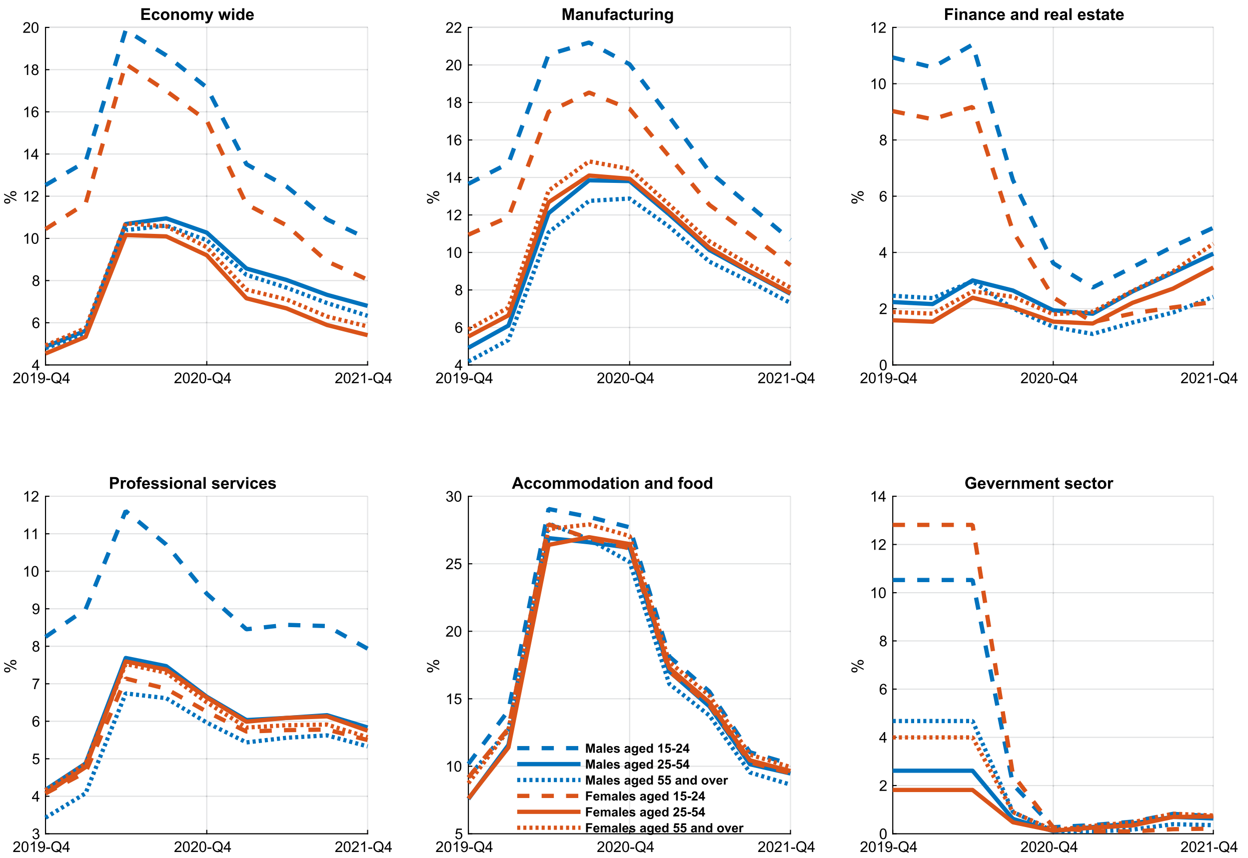

Fig. 9. Sectoral unemployment rate by sex and age (%). Note: Simulated dynamics of the unemployment rate by sex and age in the "Lockdown and supply chain crisis" scenario, at the aggregate level and for select industries. All unemployment rates are annualized.

of variables to capture additional areas of slack. For instance, the authors examine the degree of disagreement between measures to more systematically track and quantify unevenness in the labor market. By addressing the drawbacks of traditional measures, they propose a framework for assessing the labor market recovery along three different dimensions: (1) overall labor market conditions, (2) labor market inclusiveness, and (3) job characteristics.

Recent Bank work with ToTEM by Chu et al. (2020) has also shown that the Canadian workforce can be classified by occupational risk to COVID-19 as "COVID-sensitive" or "COVID-neutral." The latter is defined as those who can work from home and thus have a relatively lower exposure to COVID-19 transmission. In contrast, individuals who cannot work from home tend to have a higher risk of being exposed to COVID-19 (e.g., more face-to-face discussions, dealing with external customers, assisting and caring for others). As of August 2020, the share of "COVID-sensitive" industries was calibrated to be 43.7 percent using the VSE Risk Index, which is built upon national and provincial labor force micro-data according to occupation. It is clear that in Canada, service industries (e.g., health care, accommodation and food services, and transportation) tend to be more "COVID-sensitive," while goods industries (e.g., forestry) tend to be more "COVID-neutral."

Although the current version of CANVAS does not differentiate the labor supply elasticity of "COVID sensitive" households by modeling a relatively greater decline in their working hours in response to negative shocks, current characteristics (sectoral working hours, sex, and ages) allow for some initial exploration of the model's capacity to address labor market developments.

Our findings suggest the importance of considering household characteristics (such as sex, age, and balance sheets) in understanding their employment choices and spending patterns. The bottom panel of Fig. 9 shows that younger people (age 14–25) and women in service sectors tend to bear greater and more prolonged impacts from the pandemic.

In addition to providing the capacity to analyze household behavior by sex and age, empirical work by MacGee et al. (2020) has uncovered some Canadian evidence by constructing wealth, debt, and income for a set of households using the Survey of Financial Security. They show different effects on households across the income distribution. Low-income households have the highest risk of unemployment, but the government transfer provided a relatively high replacement of previous income. Middle-income households that lost jobs saw the fastest rise in debt, as transfers only partially replaced income lost due to unemployment. High-income households had a lower probability of unemployment in this crisis and, on average, accumulated unplanned savings. The implication of unemployment by income level of households is not explored in our current version of analysis in CANVAS. We leave this for future research.

6. Conclusion

Central banks around the world have made a generational effort to improve macroeconomic models' ability to explain macroeconomic data as well as to expand their capacity to address a growing variety of pertinent policy questions. The ever-enriching structure of these policy models and the enhanced estimation techniques have contributed to a significant improvement in their forecasting performance. Nevertheless, areas such as introducing both household and firm heterogeneity in large-scale models, modeling realistic behavior of individuals and firms, as well as addressing nonlinearities have proven to be extremely challenging for both theoretical development and computational execution.

These limitations have motivated us to devote effort into developing a behavioral macroeconomic agent-based model—CANVAS, and apply it to analyze Canadian data. The goal of our development focuses on incorporating policy-relevant advances in economic modeling, as well as improving the model's forecasting ability to complement the current suite of macroeconomic models used in the central bank community.

In this paper, we describe CANVAS's most important features, which include very detailed modeling of the Canadian economic structures using micro-data and improvements in the modeling of agents' behavior through adaptive learning. More specifically, CANVAS's structure effectively encompasses both detailed national accounting of all individual households and firms' balance sheets. Leveraging a more granular level of heterogeneity offers elaborate modeling of demographic data such as sex, age, occupation, and household balance sheets. These new features allow us to explore a broader range of policy questions and perform policy scenario analysis, such as understanding the unevenness in both production and pricing behavior of firms during the COVID-19 pandemic and recovery. In addition to providing the capacity to understand dynamics from detailed production networks, CANVAS also helps shed some light on labor markets and the evolution of various inflation measures in Canada. Finally, the detailed structure of the model has also contributed to a significant improvement in the forecasting performance of the model.

There are several potential areas of development with CANVAS. For example, heterogeneous learning, such as modeling extrapolative expectations, can be expanded from inflation to asset prices. Ongoing work focuses on developing an enriched labor market featuring migration and sectoral reallocation following shocks that induce structural changes (such as climate policies). Lastly, one could further enhance financial frictions to analyze the efficacy of extended monetary policies, such as quantitative easing and forward guidance, jointly. All of these constitute our medium-term modeling efforts.

Appendix A. Model detailed descriptions

A.1. Households

The household sector consists of all employed, unemployed, and inactive persons in Canada who are 15 years of age or older, with respective populations obtained from census data and labor force surveys. We model income heterogeneity in the household sector within the labor force. Persons in the labor force (employed and unemployed) are associated with additional characteristics, such as their age, sex, and employed industry. Employed persons supply labor to firms and receive sector-specific wages. Unemployed persons search for employment and receive unemployment benefits, which are a fraction of previously received wages. Inactive persons (e.g., pensioners) do not participate in the labor market and receive old age benefits.

Outside of the labor force, we also model heterogeneity in terms of firm ownership and transfers. We assume that each firm is owned by an "investor," who is also part of the household sector. Investors obtain dividend income from firm ownership. Each person in the model economy receives social transfers from the general government. All persons spend their income on personal consumption and residential investment.

A.1.1. Activity status

The household sector consists of a total number of H $(h = 1, 2, \dots, H)$ persons. Every person in the household sector has an *activity status*, that is, a type of economic activity from which she receives an income. The activity status is categorized into H^{act} economically active and H^{inact} economically inactive persons.[14] Economically active persons are H^W persons in the labor force, and $I + 1$ investors (the number of investors equals the number of firms and banks and is constant). Within the first set of persons in the labor force, there are $H^{\mathrm{E}}(t)$ employed and $H^{\mathrm{U}}(t)$ unemployed persons in each industry. $H^{\mathrm{E}}(t)$ and $H^{\mathrm{U}}(t)$ are endogenous since we assume that agents' employment status may switch between employed/unemployed when they are dismissed from their current job or are hired for a new position. Each person in the labor force (employed and unemployed) is also associated with additional characteristics, such as an age group, sex, and industry of employment. Economically inactive persons include persons (over the age of 15) who are not part of the labor force (e.g., retirees).

Each person in the labor force either supplies labor to a firm when employed or remains unemployed. If unemployed, the person looks for a job on the labor market from firms with open vacancies in random order and applies for a job through a *search-and-matching* process. Because the worker has occupation-specific skills, job matching occurs when the person accepts a job from the first hiring firm in the same industry as their previous employer. Search-and-matching frictions may occur: a worker remains unemployed if

[14] In this manuscript subscripts are used for indices referring to an agent in the model, while superscripts generally indicate a behavioral relation for a variable. For example, a quantity X referring to a household is denoted by X_h, expectations for a quantity X are written as X^{e}, or demand for a quantity X is indicated by X^{d}. Additionally, superscripts in capital letters are used to further distinguish related variables, e.g., $\bar{P}^{\mathrm{HH}}(t)$ denotes the consumer price index while $\bar{P}^{\mathrm{CF}}(t)$ is the capital formation price index.

there are no more open vacancies left in the same industry as her former employer. On the other hand, if there are no longer any unemployed in the industry of the searching firm, vacant positions will remain open. For simplicity, we do not consider hiring or firing costs for firms, and dismissed employees start searching for new jobs in the same period that they become unemployed.

A.1.2. Income

Every period t, each person receives income according to their activity status. Employed persons are remunerated with the wage $w_i(t)$ of firm i that provides their current employment. If the worker has changed jobs in period t, the current wage rate $w_i(t)$ would differ from wage rate $w_h(t-1)$ from the previous employer:

$$w_h(t) = \begin{cases} w_i(t) & \text{if employed by firm } i \\ w_h(t-1) & \text{otherwise.} \end{cases} \tag{8}$$

Unemployed persons receive unemployment benefits, which are a fraction (θ^{UB}) of the labor income from the last period of employment. A subset of people are investors in the model, with each investor receiving income in the form of dividends in the event that the firm she owns makes profits after interest and tax payments. There is a fixed share of economically inactive population. Each person h within this group receives social benefits sb^{inact} and does not look for a job. Additionally, we model social benefits by assuming that each person in the population receives a fixed-amount social transfer sb^{other} (such as family and childcare support, sickness benefits, etc.) from the government.

After considering all income sources, the net nominal disposable income $Y_h(t)$ of the h-th individual is defined as the sum of after-tax income and social transfers (including unemployment benefits):

$$Y_h(t) = \begin{cases} \left(w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right)+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t) & \text{if employed} \\ \left(\theta^{\mathrm{UB}}w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right)+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t) & \text{if unemployed} \\ \left(sb^{\mathrm{inact}}+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t) & \text{if not economically active} \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_i(t))+sb^{\mathrm{other}}\bar{P}^{\mathrm{HH}}(t) & \text{if investor in firm } i \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_k(t))+sb^{\mathrm{other}}\bar{P}^{\mathrm{HH}}(t) & \text{if a bank investor.} \end{cases} \tag{9}$$

A.1.3. Consumption

Each person purchases consumption goods with a certain budget constraint. Consumers' behavior is assumed to be bounded rational in that they follow a heuristic rule by consuming a fraction of their expected net disposable income ($Y_h^{\mathrm{e}}(t)$). Expected net disposable income is determined according to the household's activity status and the associated labor income stream, expected profits or social benefits and tax payments, the consumer price index of the last period, and expectations of the inflation rate $\pi^{\mathrm{e}}(t)$ formed using an AR(1) model[15] (see Equation (20)):

$$Y_h^{\mathrm{e}}(t) = \begin{cases} \left(w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right)+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if employed} \\ \left(\theta^{\mathrm{UB}}w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right)+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if unemployed} \\ \left(sb^{\mathrm{inact}}+sb^{\mathrm{other}}\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if not economically active} \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_i^{\mathrm{e}}(t))+sb^{\mathrm{other}}\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if investor in firm } i \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_k^{\mathrm{e}}(t))+sb^{\mathrm{other}}\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if a bank investor,} \end{cases} \tag{10}$$

where $\Pi_i^{\mathrm{e}}(t)$ (see Equation (44)) and

$$\Pi_k^{\mathrm{e}}(t) = \Pi_k(t-1)(1+\gamma^{\mathrm{e}}(t))(1+\pi^{\mathrm{e}}(t)) \tag{11}$$

is the expected profit based on received profits from firm i and the banking sector in the last period, respectively; τ^{INC} denotes the income tax rate, τ^{SIW} is the social insurance contribution rates to be paid by the employee, θ^{DIV} is the dividend payout ratio, and τ^{FIRM} denotes the corporate tax rate.

The consumption budget of household h ($C_h^{\mathrm{d}}(t)$) is thus given by:

$$C_h^{\mathrm{d}}(t) = \frac{\psi Y_h^{\mathrm{e}}(t)}{1+\tau^{\mathrm{VAT}}}, \tag{12}$$

where $\psi \in (0,1)$ is the propensity to consume out of expected income and τ^{VAT} is a value added tax rate on consumption.

We motivate the formulation of the consumption function by the literature of bounded rationality and lab evidence that household consumption behavior follows simple heuristics, as in Delli Gatti et al. (2011). Consumers allocate their consumption budget to purchase different goods from firms. The consumption budget of the h-th household to purchase the g-th good is

[15] As a robustness check, we allowed households to form their expectation of the inflation rate based on CPI inflation instead of GDP deflator inflation, and the differences are negligible.

$$C^{\mathrm{d}}_{hg}(t) = \frac{b^{\mathrm{HH}}_g \bar{P}_g(t-1)}{\bar{P}^{\mathrm{HH}}(t-1)} C^{\mathrm{d}}_h(t), \tag{13}$$

where b^{HH}_g is the consumption coefficient for the g-th product of households.[16]

Once households determine their consumption budget, they visit firms to purchase goods and services according to the search-and-matching mechanism (see Appendix A.2.3). Whether an individual firm can accommodate consumers' demand depends on its production and inventory stock. Thus realized consumption of household h follows:

$$C_h(t) \begin{cases} = \sum_g C^{\mathrm{d}}_{hg}(t) & \text{if consumers' demand is successfully met, and} \\ < \sum_g C^{\mathrm{d}}_{hg}(t) & \text{if all firms visited could not satisfy consumers' demand.} \end{cases} \tag{14}$$

A.1.4. Residential investment

The housing market is also modeled by a simple heuristic that each person uses a portion of their income for residential investment. Similar to Equation (12), we assume residential investment occurs according to a fixed rate ψ^{H} on expected net disposable income:

$$I^{\mathrm{d}}_h(t) = \frac{\psi^{\mathrm{H}} Y^{\mathrm{e}}_h(t)}{1+\tau^{\mathrm{CF}}}, \tag{15}$$

where τ^{CF} can be considered as property tax rate on residential investment. Demand of individual h for product g net of taxes ($I^{\mathrm{d}}_{hg}(t)$) is determined by fixed weights b^{CFH}_g:

$$I^{\mathrm{d}}_{hg}(t) = \frac{b^{\mathrm{CFH}}_g \bar{P}_g(t-1)}{\sum_g b^{\mathrm{CFH}}_g \bar{P}_g(t-1)} I^{\mathrm{d}}_h(t). \tag{16}$$

Realized sales of residential investment goods purchased by individuals are an outcome of the search-and-matching process on the housing market:

$$I_h(t) \begin{cases} = \sum_g I^{\mathrm{d}}_{hg}(t) & \text{if the individual successfully realized the investment plan, and} \\ < \sum_g I^{\mathrm{d}}_{hg}(t) & \text{if all firms visited could not satisfy its demand.} \end{cases} \tag{17}$$

The stock of residential structure owned by individual h then follows:

$$K_h(t) = K_h(t-1) + I_h(t). \tag{18}$$

It is worth mentioning that our modeling choice of residential investment is subject to some limitations. Notably, we don't differentiate borrower households from saver households, therefore abstract from residential mortgages and related household indebtedness. Given collateralized household debt (that consists of residential mortgages and home equity lines of credit) accounts for more than 80 percent of total household debt in Canada, this simplification will underestimate the role of shock propagation on household consumption. In an extension of this paper, we are leveraging Canadian household microdata (e.g., Survey of Households Spending data (SHS), Survey of Financial Security (SFS), etc.) to introduce a distribution of households in CANVAS to analyze key model properties (including redistributional effects of household heterogeneity in inflation and consumption).

A.1.5. Savings

Savings in period t is the difference between current disposable income $Y_h(t)$ and realized consumption expenditure $C_h(t)$ that includes realized housing investment $I_h(t)$. Savings are used to accumulate financial wealth[17]:

$$\begin{aligned} D_h(t) = D_h(t-1) + &\underbrace{Y_h(t) - (1+\tau^{\mathrm{VAT}})C_h(t) - (1+\tau^{\mathrm{CF}})I_h(t)}_{\text{Savings}} \\ &+ \underbrace{\bar{r}(t)\max(0, D_h(t-1))}_{\text{Interest received}} - \underbrace{r(t)\max(0, -D_h(t-1))}_{\text{Interest payments}} \end{aligned} \tag{19}$$

The stock of deposits therefore reflects interest payments on overdrafts of the household's deposit account ($D_h(t-1) < 0$) and interest received on deposits held with the bank ($D_h(t-1) > 0$).[18]

[16] Similar to how the Consumer Price Index (CPI) is measured in Canada, we assume all households buy the same set of goods, independent of the amount they spend on consumption. The consumption basket includes all goods and services purchased by households in Canada, including the groceries households buy, the electricity and water rates they pay, the haircuts they get, the hotels they stay in, etc. In CPI calculations, each item in the households' consumption basket receives a relative importance, or basket weight, that represents the proportion households' spend on each item. For example, a much larger share of Canadians' spending goes to gasoline than to milk; therefore, gasoline will receive a larger weight than milk in the CPI basket. We rely on Canadian input-output tables to calibrate these weights and will provide a detailed discussion in Section 3.

[17] Savings can also be negative in our model, in which case the person h would decumulate her financial wealth to finance her consumption needs.

[18] We assume that these interest payments or receipts do not enter the household's consumption decision and thus generate no wealth effects on consumption.

A.2. Firms

The firm sector is populated by heterogeneous agents that represent all firms from every industry in the Canadian economy. The firm population of each industry s is obtained from business demography data, and the size distribution is chosen to approximately correspond to the firm size distribution in Canada (for details, see Section 2).

There are s ($s = 1, 2, \dots, S$) industries populated with I_s firms in each industry. Each firm i ($i = 1, 2, \dots, I = \sum_s I_s$) produces a principal product g ($g = 1, 2, \dots, G$) using labor, capital, and intermediate inputs from other firms.[19]

A.2.1. Firms' expectations for aggregate economy

Firms' expectations regarding economic growth and inflation are formed using simple but optimal AR(1) forecasting heuristics.[20] Agents learn the optimal AR(1) rules with parameters consistent with two observable statistics, the sample mean and the first-order sample autocorrelation (Hommes and Zhu (2014)). Equation (20) summarizes the firm's expectations of the real GDP growth rate ($\gamma^e(t)$) and inflation ($\pi^e(t)$), measured by log first difference of the GDP deflator:

$$\gamma^e(t) = \mathrm{e}^{\alpha^\gamma(t-1)\gamma(t-1)+\beta^\gamma(t-1)+\epsilon^\gamma(t-1)} - 1 \tag{20a}$$

$$\pi^e(t) = \mathrm{e}^{\alpha^\pi(t-1)\pi(t-1)+\beta^\pi(t-1)+\epsilon^\pi(t-1)} - 1, \tag{20b}$$

where parameters $\alpha^\gamma(t-1)$, $\alpha^\pi(t-1)$, $\beta^\gamma(t-1)$, and $\beta^\pi(t-1)$ are re-estimated every period with the time series of output growth $\gamma(t')$ and inflation $\pi(t')$ where $t' = -T', -T'+1, -T'+2, \dots, 0, 1, 2, \dots, t-1$. $\epsilon^\gamma(t-1)$, and $\epsilon^\pi(t-1)$ are random shocks with zero mean and variance re-estimated every period from past observations over the last $T' + t - 1$ periods.

In a complex environment of fundamental uncertainty and imperfect information, obtaining accurate forecasts is nearly impossible. Firms in such a complex environment may choose simple forecasting methods that closely monitor the relevant variables, even if such methods fail to understand the complete model of the economy. This approach fits within the concept of procedural rationality (Gigerenzer, 2015). A forecasting method that meets these requirements is the AR(1) forecasting rule: this is a simple procedure for projecting past trends into the future while its forecasting capabilities are relatively high.

Under adaptive learning, the gaps between expected and realized values of state variables will close gradually. This ensures that the unconditional mean and autocorrelations of the unknown non-linear stochastic process—which describe the actual law of motion of the model economy—concur with the unconditional mean and autocorrelations of the AR(1) process in the long run. In fact, adaptive learning with the AR(1) rule leads to convergence to a behavioral learning equilibrium (BLE) in the complex ABM economy, one of the simplest types of misspecification equilibrium put forth in the adaptive learning literature (Hommes and Zhu, 2014).

A.2.2. Production

In each period t, firm i from industry s produces real output ($Y_i(t)$) of a principal product g with Leontief technology that combines intermediate goods, labor and capital, labor input ($N_i(t)$, in the number of persons employed), real intermediate goods/services and raw materials ($M_i(t)$), as well as real capital ($K_i(t-1)$):

$$Y_i(t) = \min\left(Q_i^{\mathrm{s}}(t), \beta_i M_i(t), \alpha_i(t) N_i(t), \kappa_i K_i(t-1)\right), \tag{21}$$

where $\alpha_i(t)$ is the labor-specific productivity of firm $i \in I_s$ (see Equation (25)) and β_i and κ_i are productivity coefficients for intermediate inputs and capital, respectively.[21]

Demand for labor Each firm i uses labor input $N_i(t)$ for production where employment is measured by the number of persons employed. Demand for labor in time t, $N_i^{\mathrm{d}}(t)$, is determined according to the firm's desired scale of activity ($Q_i^{\mathrm{s}}(t)$) and its average labor productivity ($\bar{\alpha}_i$):

$$N_i^{\mathrm{d}}(t) = \max\left(1, \mathrm{round}\left(\frac{\min\left(Q_i^{\mathrm{s}}(t), \kappa_i K_i(t-1)\right)}{\bar{\alpha}_i}\right)\right). \tag{22}$$

We introduce some simple heuristics here to characterize firms' behavior. We consider four different scenarios: (1) if the additional labor demand of firm i is less than a half-time position, labor demand is left unchanged; (2) if the additional production needs of the firm i exceed a half-time occupation, a new employee is hired; (3) if the operating workforce at the beginning of period t ($N_i(t-1)$), i.e., the number of persons employed in $t-1$, is higher than the desired workforce, the firm fires $N_i(t-1) - N_i^{\mathrm{d}}(t)$ randomly chosen employees (accounting for production constraints due possibly to a shortage of capital); and (4) if the demand for labor to reach the desired scale of activity is greater than the operating workforce, the firm posts labor vacancies.

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[19] We assume a one-to-one correspondence between the sets of industries s and products g, meaning that the n-th sector produces only the n-th good, and $S = G$. Formally, the correspondence between goods g being produced in sector s would be represented by a unity matrix.

[20] This modeling choice is comparable to other adaptive mechanisms, such as VAR expectations as used in the US Federal Reserve's FRB/US macroeconomic model (Brayton et al., 1997), or expectations according to an exponential moving average (EMA) model, as in Assenza et al. (2015a).

[21] The assumption of a Leontief production technology is consistent with the data and is in line with the literature (Assenza et al., 2015a). Moreover, as our explicit aim was to derive the simplest possible ABM that has the features we desire, we relegate all further extensions of the model, such as assumptions on technological progress that change technology coefficients, to further research.

The demand for new labor can be represented as:

$$V_i(t) = N_i^{\mathrm{d}}(t) - N_i(t-1). \tag{23}$$

Recalling the process of individuals' seeking employment, where whether vacancies are filled or not depends on the search-and-matching mechanism in the labor market (see Appendix A.1.1), we obtain labor input:

$$N_i(t) \begin{cases} = N_i^{\mathrm{d}}(t) & \text{if firm } i \text{ successfully fills all vacancies, and} \\ < N_i^{\mathrm{d}}(t) & \text{if there are unfilled vacancies.} \end{cases} \tag{24}$$

As employees are either employed full-time, part-time, or work overtime, the average productivity of labor $\alpha_i(t)$ of firm i reflects the distribution of hours worked by all employees:

$$\alpha_i(t) = \bar{\alpha}_i \min\left(1.5, \frac{\min\left(Q_i^{\mathrm{s}}(t), \beta_i M_i(t-1), \kappa_i K_i(t-1)\right)}{N_i(t)\bar{\alpha}_i}\right), \tag{25}$$

where the maximum work effort is 150 percent of a full position (which is the maximum working time legally allowed in Canada for a limited duration). To remunerate increased or decreased work effort as compared to a full-time position, the average wage $\bar{w}_i$ of firm i is set accordingly:

$$w_i(t) = \bar{w}_i \min\left(1.5, \frac{\min\left(Q_i^{\mathrm{s}}(t), \beta_i M_i(t-1), \kappa_i K_i(t-1)\right)}{N_i(t)\bar{\alpha}_i}\right), \tag{26}$$

where $w_i(t)$ is the real wage paid by firm i.[22]

Demand for capital goods and business investment Each period, the i-th firm chooses real investment ($I_i^{\mathrm{d}}(t)$), which adjusts the real capital stock $K_i(t)$. As in standard DSGE models, capital adjustment in CANVAS is not immediate and is time-consuming.

New capital goods acquired at the time t become part of the capital stock only in the next period $t+1$. This makes capital a durable and sticky input. The desired business investment in period t is

$$I_i^{\mathrm{d}}(t) = \frac{\delta_i}{\kappa_i} \min\left(Q_i^{\mathrm{s}}(t), \kappa_i K_i(t-1)\right), \tag{27}$$

where δ_i is a firm-specific capital depreciation rate. The capital stock, as an aggregate of all goods g, evolves according to depreciation rates and the investment law of motion:

$$K_i(t) = K_i(t-1) - \frac{\delta_i}{\kappa_i} Y_i(t) + I_i(t). \tag{28}$$

The firms' business investment decision process is modeled by a simple heuristic that accounts for both expectations of the aggregate economy and firm-specific conditions. Each period, firm i observes realized demand and makes a forecast of future demand according to the expected rate of economic growth. Conditional on demand for business investment, the firm's capital stock adjusts accordingly when accounting for depreciation. Under adaptive learning, should realized growth rates surpass growth expectations, investment in subsequent periods will adapt to the approximate trend equilibrium level, and vice versa. As a result, the resulting trend of business investment tends to approximate the trend equilibrium path of this model economy.

We assume a homogeneous capital stock for all firms and thus fixed weights b_g^{CF}, namely, each firm i—irrespective of the sector s firm i is part of—demands $b_g^{\mathrm{CF}} I_i^{\mathrm{d}}(t)$ as its real investment from firms producing good g:

$$I_{ig}^{\mathrm{d}}(t) = b_g^{\mathrm{CF}} I_i^{\mathrm{d}}(t). \tag{29}$$

Realized business investment depends on the search-and-matching process on the capital goods market (see Appendix A.2.3):

$$I_i(t) \begin{cases} = \sum_g I_{ig}^{\mathrm{d}}(t) & \text{if the firm successfully realized the investment plan, and} \\ < \sum_g I_{ig}^{\mathrm{d}}(t) & \text{if all firms visited could not satisfy its demand} \end{cases} \tag{30}$$

In the case where firm i cannot realize its investment plan, it will have to scale down future activity (see Equation (21)).

Demand for intermediate inputs Each firm needs intermediate inputs for production. We assume that firm i holds an inventory stock of input goods $M_i(t)$ (in real terms) for each type of good g. Each period, the firm follows a heuristic of maintaining its inventory stock in positive supply and choosing the desired amount of intermediate goods and raw materials ($\Delta M_i^{\mathrm{d}}(t)$) to avoid shortfalls of material input that would impede production:

$$\Delta M_i^{\mathrm{d}}(t) = \frac{\min\left(Q_i^{\mathrm{s}}(t), \kappa_i K_i(t-1)\right)}{\beta_i} \tag{31}$$

[22] This differs from the nominal wage rate that affects households' disposable income; see Appendix A.1.2.

where the sector-specific technology, a_{sg}, is given by

$$\Delta M^{\mathrm{d}}_{ig}(t) = a_{sg} \Delta M^{\mathrm{d}}_{i}(t) \quad \forall i \in I_s. \tag{32}$$

The realized demand for intermediate goods depends on a search-and-matching process (see Appendix A.2.3):

$$\Delta M_i(t) \begin{cases} = \sum_g \Delta M^{\mathrm{d}}_{ig}(t) & \text{if the firm successfully realized its plan, and} \\ < \sum_g \Delta M^{\mathrm{d}}_{ig}(t) & \text{if all firms visited could not satisfy its demand.} \end{cases} \tag{33}$$

If firm i does not succeed in acquiring the materials it intends to purchase, it will be limited in its production possibilities. The inventory stock of intermediate inputs evolves according to the material use in production and realized acquisitions of new intermediate goods:

$$M_i(t) = M_i(t-1) - \frac{Y_i(t)}{\beta_i} + \Delta M_i(t). \tag{34}$$

For simplicity, we assume that the raw material stock does not depreciate since firms have a steady use.

A.2.3. Sales

Demand for products of firm i consist of three sources: (1) final consumption goods, (2) capital goods, as well as (3) material or intermediate input goods. Firms face uncertainty regarding the main determinants of their individual success on the market: future sales, market prices, the availability of inputs for the production process (labor, capital, intermediate inputs), wages, cash flow, and their access to external finance, among others, are unknown. Consequently, each firm has to form expectations about the future that may not correspond to actual realizations. We elaborate on the modeling of these aspects in the following section.

Firms face demand from other agents, including (1) an individual h, (2) the government j, and (3) another firm demanding capital or intermediate input goods. Consumption demand $Q^{\mathrm{d}}_i(t)$ is determined only after the firm has set its price and carried out production plan $Y_i(t)$. The process of firm i generating sales is modeled by a search-and-matching mechanism specifying the product supply relative to the demand of consumers:

$$Q^{\mathrm{d}}_i(t) \begin{cases} < Y_i(t) + S_i(t-1) & \text{if demand from consumers is smaller than supply from firm } i, \\ = Y_i(t) + S_i(t-1) & \text{if demand from consumers exactly matches supply from firm } i, \text{ and} \\ > Y_i(t) + S_i(t-1) & \text{if demand from consumers is larger than supply from firm } i, \end{cases} \tag{35}$$

where $S_i(t-1)$ is the inventory of finished goods.

In this search-and-matching process, every consumer searches for the best bargain for each of products g to satisfy its demand. The best bargain is characterized as a successful matching at a product's lowest market price. The consumption demand and supply in the model are formed within the firm's network: in each period, consumers visit a number of randomly chosen foreign or domestic firms that sell the good g (see Appendix A.6.1 for details on foreign firms). The total probability of firm i being selected in this process, $pr^{\mathrm{cum}}_i(t)$, is the average of two probabilities: (1) the probability of firm i being selected due to its offering price $pr^{\mathrm{price}}_i(t)$; and (2) the probability of being chosen conditional on firm i's relative size to other firms $pr^{\mathrm{size}}_i(t)$:

$$pr^{\mathrm{price}}_i(t) = \frac{e^{-2P_i(t)}}{\sum_{i \in I_{s=g}} e^{-2P_i(t)}}$$

$$pr^{\mathrm{size}}_i(t) = \frac{Y_i(t)}{\sum_{i \in I_{s=g}} Y_i(t)}$$

$$pr^{\mathrm{cum}}_i(t) = \frac{pr^{\mathrm{price}}_i(t) + pr^{\mathrm{size}}_i(t)}{2}$$

where $Y_i(t)$ is the production of goods by firm i (see Equation (21)). Since the probability of a firm being selected is a function of the size and offering price, a firm charging a relatively lower price than its competitors is more likely to be picked by consumers and generate sales. Similarly, a larger firm tends to have a higher probability to be picked by consumers. After the consumer identifies the firm to purchase from, it satisfies all its demand with the first firm. When the consumer discovers that the most preferred firm is in short supply, she resorts to the remaining firms to ensure all demand can be met by a firm. If a consumer does not succeed in satisfying her demand for a specific product g, she saves involuntarily within this period.

Thus sales are the realized demand, which is the lesser of (1) firm i's total supply of goods, $Q^{\mathrm{o}}_i(t)$, and (2) consumer demand, $Q^{\mathrm{d}}_i(t)$:

$$Q_i(t) = \min(Q^{\mathrm{o}}_i(t), Q^{\mathrm{d}}_i(t)), \tag{36}$$

where $Q^{\mathrm{o}}_i(t) = Y_i(t) + S_i(t-1)$ denotes total supply at time t, which consists of production in the current period, $Y_i(t)$ and the inventory from last period, $S_i(t-1)$.

As a reflection of firms' expectation error concerning demand, "excess supply" is defined as the difference between production and sales:

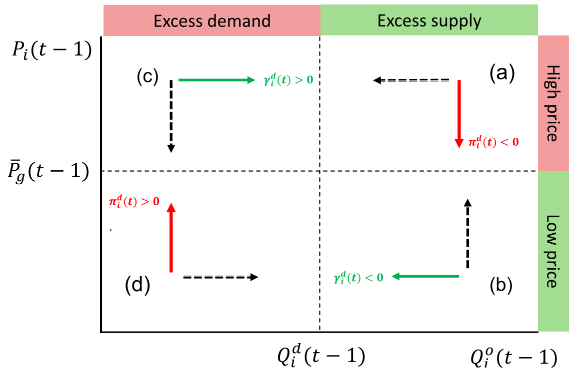

Fig. 10. Firm quantity and price setting.

$$\Delta S_i(t) = (1 - \delta_i^S)(Y_i(t) - Q_i(t)), \tag{37}$$

where δ_i^S is the depreciation rate of inventories. The stock of inventories evolves as excess supply accumulates over time, following

$$S_i(t) = S_i(t-1) + \Delta S_i(t). \tag{38}$$

At the next period, accumulated inventories are combined together with newly produced goods as goods supply.

A.2.4. Price and quantity setting

Firms set prices and determine supply based on the expectations for aggregate economic growth and inflation, as well as market expectations for the specific product they supply g.

Aggregate expectations under behavioral learning equilibrium Firms' expectations of the real GDP growth rate ($\gamma^e(t)$) and inflation ($\pi^e(t)$) are measured by log first difference of the GDP deflator. Consider an example of excess demand at time t where a firm realizes that the realized growth rates have exceeded its expected growth expectations last period. Recognizing its forecasting error from last period, it will start increasing production to meet the demand. Production is increased to a point where supply and demand will converge to equilibrium. In contrast, when firms discover they have excess supply where realized growth falls short of expectations, firms will gradually reduce production in order to avoid excessive inventories. Similar to production quantity adjustment, firms can also adjust their prices to facilitate the convergence to equilibrium.

Should a smaller or larger shock—such as an (endogenous) bankruptcy of a firm or an exogenous demand or supply shock (e.g., the COVID-19 pandemic or an export shock)—pull the economy off the trend, path dependencies might ensue that change the long-term BLE of this model economy. However, after the medium to long turn, adaptive learning will steer the model toward this new BLE, as can be observed in our applications to the economic effects of the lockdown following COVID-19 pandemic (see Section 5).

Firm-specific expectations with simple heuristics In addition to setting their expectations of the general economy (in terms of GDP growth and inflation), firm i also chooses to alter their previous period's quantity or price based on their perceived market conditions. We assume that due to asymmetric information and search costs, each firm has a certain degree of pricing power in their local market, so that the law of one price does not apply. We also assume that firms cannot change their quantity and price at the same time.[23]

Firms form their expectations of market conditions using two indicators that both rely on observed information from the previous period $t-1$: (1) the level of excess supply, which is the difference between the previous period's supply $Q_i^o(t-1)$ and realized demand $Q_i^d(t-1)$; and (2) the deviation of the firm's price $P_i(t-1)$ from the average price among competitors $\bar{P}_g(t-1)$ for product g. Each firm considers four possible price-quantity setting scenarios (depicted in Fig. 10):

a) If there is excess supply and the charged price is higher than market average, reduce the price and maintain the production.
b) If there is excess supply and the charged price is lower than market average, maintain the price and reduce the production.
c) If there is excess demand and the charged price is higher than market average, maintain the price and increase the production.
d) If there is excess demand and the charged price is lower than market average, increase the price and maintain the production.

[23] This modeling choice is adapted from Delli Gatti et al. (2011), who use a similar price-quantity heuristic and is motivated by empirical surveys of managers' pricing and quantity decisions; see, e.g., Kawasaki et al. (1982) and Bhaskar et al. (1993). Moreover, there is empirical evidence from laboratory studies showing subjects use similar price-quantity settings heuristics in monopolistic price-quantity settings (see, e.g., Assenza et al. (2015b)).

Effectively, the growth rate of quantity only varies from zero in scenarios (b) and (c):

$$\gamma_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^{\text{o}}(t-1)} - 1 & \text{if } Q_i^{\text{o}}(t-1) \leq Q_i^d(t-1) \text{ and } P_i(t-1) \geq \bar{P}_g(t-1) \\ & \text{or if } Q_i^{\text{o}}(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{39}$$

Firm i's supply choice depends on its expectations of the aggregate economy and individual supply/demand versus pricing power. In our model, it is driven by three sources: (1) its product supply from last period $Q_i^{\text{o}}(t-1)$; (2) the expected, economy-wide economic growth rate ($\gamma^e(t)$); and (3) the realized, firm-specific growth rate of quantity from the previous period, $\gamma_i^d(t)$:

$$Q_i^{\text{s}}(t) = Q_i^{\text{o}}(t-1)(1+\gamma^e(t))(1+\gamma_i^d(t)). \tag{40}$$

Similar to Equation (39), firms adjust their prices in the following manner:

$$\pi_i^d(t) = \begin{cases} \frac{Q_i^d(t-1)}{Q_i^{\text{o}}(t-1)} - 1 & \text{if } Q_i^{\text{o}}(t-1) \leq Q_i^d(t-1) \text{ and } P_i(t-1) < \bar{P}_g(t-1) \\ & \text{or if } Q_i^{\text{o}}(t-1) > Q_i^d(t-1) \text{ and } P_i(t-1) \geq \bar{P}_g(t-1) \\ 0 & \text{otherwise.} \end{cases} \tag{41}$$

Inflation determination With some aggregation and simplification, firm i's nominal price $P_i(t)$ in our model can be decomposed to three components: (1) expectations of economy-wide inflation $\pi^e(t)$ (aggregate inflation expectation); (2) the cost structure of the firm $\pi_i^c(t)$ (cost-push inflation); and (3) the change from the previous period's price $\pi_i^d(t)$ (demand-pull inflation):

$$P_i(t) = P_i(t-1) \cdot \underbrace{(1+\pi_i^d(t))}_{\substack{\text{Demand-pull}\\ \text{inflation}}} \cdot \underbrace{(1+\pi_i^c(t))}_{\substack{\text{Cost-push}\\ \text{inflation}}} \cdot \underbrace{(1+\pi^e(t))}_{\substack{\text{Aggregate}\\ \text{inflation expectation}}} \tag{42}$$

We define the cost-push inflation $\pi_i^c(t)$ as:

$$\pi_i^c(t) = \underbrace{\frac{(1+\tau^{SIF})\bar{w}_i}{\bar{\alpha}_i}\left(\frac{\bar{P}^{HH}(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit labor costs}} + \underbrace{\frac{1}{\beta_i}\left(\frac{\sum_g a_{sg}\bar{P}_g(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit production material costs}} + \underbrace{\frac{\delta_i}{\kappa_i}\left(\frac{\bar{P}^{CF}(t-1)}{\bar{P}_{g=s}(t-1)} - 1\right)}_{\text{Unit capital costs}} \quad \forall i \in I_s \tag{43}$$

where, $\bar{\alpha}_i$ indicates the average labor productivity and $\bar{w}_i$ is the average real wage, defined as gross wages, which include both salary costs and employers' contributions to social insurance charged with a rate τ^{SIF}. $\frac{1}{\beta_i}\sum_g a_{sg}$ is real unit expenditures on intermediate production input by industry s on good g, weighted by the average product price index $\bar{P}_g(t)$ (see Equation (49)). δ_i/κ_i are unit capital costs, conditional on the average price of capital goods ($\bar{P}^{CF}(t)$) and capital depreciation relative to productivity growth (where δ_i is the firm-specific capital depreciation rate and κ_i is the productivity coefficient for capital).

A.2.5. Financial linkage

External finance The firm's expectation for its profit is determined with a heuristic:

$$\Pi_i^{\text{e}}(t) = \Pi_i(t-1)(1+\gamma^{\text{e}}(t))(1+\pi^{\text{e}}(t)), \tag{44}$$

where firm i's expected profit $\Pi_i^{\text{e}}(t)$ is based on (1) the profit in the previous period, $\Pi_i(t-1)$; (2) the expected, economy-wide economic growth rate ($\gamma^e(t)$); and (3) aggregate inflation expectations $\pi^e(t)$ ("n").

Thus, each firm i forms an expectation on its future cash flow $\Delta D_i^{\text{e}}(t)$, that is, the expected change of deposits $D_i(t)$:

$$\Delta D_i^{\text{e}}(t) = \underbrace{\Pi_i^{\text{e}}(t)}_{\text{Exp. profit}} - \underbrace{\theta L_i(t-1)}_{\text{Debt instalment}} - \underbrace{\tau^{\text{FIRM}}\max(0,\Pi_i^{\text{e}}(t))}_{\text{Corporate taxes}} - \underbrace{\theta^{\text{DIV}}(1-\tau^{\text{FIRM}})\max(0,\Pi_i^{\text{e}}(t))}_{\text{Dividend payout}}, \tag{45}$$

where θ is the rate of debt instalment on firm i's outstanding loans $L_i(t-1)$, τ^{FIRM} is the corporate tax rate, and θ^{DIV} is the dividend payout ratio. If the internal financing from profits are insufficient to finance the firm's expenditures, it seeks external financial resources to finance current or future expenditures. New credit (in form of bank loans) $\Delta L_i^{\text{d}}(t)$ is determined as:

$$\Delta L_i^{\text{d}}(t) = \max(0, -\Delta D_i^{\text{e}}(t) - D_i(t-1)). \tag{46}$$

The availability of bank credit depends on the capitalization of the banking sector and the arrival of firms to ask for a loan (see Appendix A.5.1 for details). If the firm cannot obtain a loan on the credit market, it might become credit constrained (see Equation (75)). If the firm does not obtain the desired loan, it may become insolvent (see Equation (54)).

Accounting Firm profits $\Pi_i(t)$ are an accounting measure that is defined as revenues from sales plus changes in inventories minus expenditures on labor, material, depreciation, interest payments, and taxes:

$$\begin{aligned}\Pi_i(t) = {} & \underbrace{P_i(t)Q_i(t)}_{\text{Sales}} + \underbrace{P_i(t)\Delta S_i(t)}_{\text{Inventory change}} \underbrace{-(1+\tau^{\mathrm{SIF}})w_i(t)N_i(t)\bar{P}^{\mathrm{HH}}(t)}_{\text{Labor costs}} \\ & \underbrace{-\frac{1}{\beta_i}\bar{P}_i(t)Y_i(t)}_{\text{Material costs}} - \underbrace{\frac{\delta_i}{\kappa_i}P_i^{\mathrm{CF}}(t)Y_i(t)}_{\text{Depreciation}} - \underbrace{\tau_i^{\mathrm{Y}}P_i(t)Y_i(t) - \tau_i^{\mathrm{K}}P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on products/production}} \\ & \underbrace{-r(t)(L_i(t-1)+\max(0,-D_i(t-1)))}_{\text{Interest payments}} + \underbrace{\bar{r}(t)\max(0,D_i(t-1))}_{\text{Interest received}},\end{aligned} \tag{47}$$

where $r(t)$ is the interest rate paid on outstanding loans (see Equation (77)). $\bar{P}_i(t)$ and $P_i^{\mathrm{CF}}(t)$ are the actual prices paid by firm i for intermediate goods and investment in capital goods, respectively, which are both an outcome of the search-and-matching process. $\bar{P}^{\mathrm{HH}}(t)$ is the consumer price index (CPI):

$$\bar{P}^{\mathrm{HH}}(t) = \sum_g b_g^{\mathrm{HH}}\bar{P}_g(t), \tag{48}$$

where b_g^{HH} is the household consumption coefficient for product g and $\bar{P}_g(t)$ is the producer price index for the principal good g:

$$\bar{P}_g(t) = \frac{\sum_{i\in I_{s=g}} P_i(t)Q_i(t) + P_{m=g}(t)Q_{m=g}(t)}{\sum_{i\in I_{s=g}} Q_i(t) + Q_{m=g}(t)}. \tag{49}$$

Firm net cash flow reflects the amount of liquidity moving in or out of its deposit account:

$$\begin{aligned}\Delta D_i(t) = {} & \underbrace{P_i(t)Q_i(t)}_{\text{Sales}} - \underbrace{(1+\tau^{\mathrm{SIF}})w_i(t)N_i(t)\bar{P}^{\mathrm{HH}}(t)}_{\text{Labor costs}} - \underbrace{\bar{P}_i(t)\Delta M_i(t)}_{\text{Material costs}} \\ & - \underbrace{\tau_i^{\mathrm{Y}}P_i(t)Y_i(t) - \tau_i^{\mathrm{K}}P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on products and production}} \underbrace{-\tau^{\mathrm{FIRM}}\max(0,\Pi_i(t))}_{\text{Corporate tax payments}} \\ & \underbrace{-\theta^{\mathrm{DIV}}(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_i(t))}_{\text{Dividend payments}} \underbrace{-r(t)(L_i(t-1)+\max(0,-D_i(t-1)))}_{\text{Interest payments}} \\ & \underbrace{+\bar{r}(t)\max(0,D_i(t-1))}_{\text{Interest received}} - \underbrace{P_i^{\mathrm{CF}}(t)I_i(t)}_{\text{Investment costs}} + \underbrace{\Delta L_i(t)}_{\text{New credit}} - \underbrace{\theta L_i(t-1)}_{\text{Debt instalment}}.\end{aligned} \tag{50}$$

Furthermore, firm i pays interest on outstanding loans and overdrafts on firm i's deposit account (in case $D_i(t) < 0$) at the same rate $r(t)$, which includes the bank's markup rate. In the opposite case, when the firm holds (positive) deposits with the bank (i.e., $D_i(t) > 0$), the interest rate received is lower and corresponds to the policy rate set by the central bank (see Appendix A.5).

Firm deposits are then previous deposits plus net cash flow:

$$D_i(t) = D_i(t-1) + \Delta D_i(t). \tag{51}$$

Similarly, overall debt is updated as follows:

$$L_i(t) = (1-\theta)L_i(t-1) + \Delta L_i(t). \tag{52}$$

Finally, firm equity $E_i(t)$ evolves as the balancing item on the firm's balance sheet, where all stocks are accounted for mark-to-market:

$$E_i(t) = D_i(t) + \sum_g a_{sg}\bar{P}_g(t)M_i(t) + P_i(t)S_i(t) + \bar{P}^{\mathrm{CF}}(t)K_i(t) - L_i(t) \quad \forall i \in I_s. \tag{53}$$

$\bar{P}^{\mathrm{CF}}(t)$ is the capital goods price index (CGPI), defined as

$$\bar{P}^{\mathrm{CF}}(t) = \sum_g b_g^{\mathrm{CF}}\bar{P}_g(t), \tag{54}$$

where b_g^{CF} is the capital formation coefficient for product g.

Insolvency If a firm is cash flow insolvent (i.e., $D_i(t) < 0$) and balance sheet insolvent (i.e., $E_i(t) < 0$) at the same time, it goes bankrupt. For simplicity, we maintain the total firms' distribution by assuming that the bankrupted firm is replaced by a new firm that enters the market in the same period. We assume that the real capital stock of the bankrupt firm is left to the entrant firm at zero costs, but that the new firm has to take over a part of the bankrupt firm's liabilities. Therefore, a part of loans taken out by the bankrupt firm is written off so that the remaining liabilities of firm i amount to a fraction ζ^{b} of its real capital stock. After this partial debt cancellation, the remaining liabilities of the bankrupt firm are transferred to the balance sheet of the entrant firm. In the next period $(t+1)$ liabilities of firm i are initialized with

$$L_i(t+1) = \zeta^{\mathrm{b}} \bar{P}_i^{\mathrm{CF}}(t) K_i(t) \tag{55}$$

and firm deposits with

$$D_i(t+1) = 0. \tag{56}$$

Correspondingly, in the next period $(t+1)$ equity of the new firm i is initialized with

$$E_i(t+1) = E_i(t) + \left(L_i(t) - D_i(t) - \zeta^{\mathrm{b}} \bar{P}_i^{\mathrm{CF}}(t) K_i(t)\right). \tag{57}$$

A.3. Monetary policy

The central bank (CB) sets the policy rate $\bar{r}(t)$ based on implicit inflation and growth targets, provides liquidity to the banking system (advances to the bank), and takes deposits from the bank in the form of reserves deposited at the central bank. Furthermore, the central bank purchases external assets (government bonds) and thus acts as a creditor to the government.

A.3.1. Policy rule

The policy rate is determined by an augmented Taylor rule (Taylor, 1993), where the central bank agent learns the optimal parameters. Following Blattner and Margaritov (2010), we include forecasted quarter-over-quarter inflation and real GDP growth in the reaction function:

$$\bar{r}(t) = \rho(t-1)\bar{r}(t-1) + (1-\rho(t-1))(r^*(t-1) + \pi^* + \xi^\pi(t-1)(\pi^e(t) - \pi^*) + \xi^\gamma(t-1)\gamma^e(t)), \tag{58}$$

where $\rho(t-1)$ is the interest rate smoothing parameter that reflects the gradual adjustment to the policy rate, $r^*(t-1)$ is the real equilibrium interest rate, π^* is the inflation target, $\xi^\pi(t-1)$ is the policy parameter on inflation deviations from the target, and $\xi^\gamma(t-1)$ is the weight on the forecasted real GDP growth rate. $\rho(t-1)$, $r^*(t-1)$, $\xi^\pi(t-1)$, and $\xi^\gamma(t-1)$ are re-estimated every period on time series of the real GDP growth rate $\gamma(t')$, inflation $\pi(t')$, and $\bar{r}(t')$ where $t' = -T', -T'+1, -T'+2, \ldots, 0, 1, 2, \ldots, t-1$. As initial conditions for $t' = -T', -T'+1, -T'+2, \ldots, 0$, we use the log differences of real GDP, the GDP deflator (inflation), as well as the Bank of Canada's policy interest rate.

A.3.2. Central bank balance sheet

The central bank's profits $\Pi^{\mathrm{CB}}(t)$ are computed as the difference between revenues from interest payments on government debt, as well as revenues $(D_k(t) < 0)$ or costs $(D_k(t) > 0)$ due to the net position in advances/reserves vis-à-vis the banking system:

$$\Pi^{\mathrm{CB}}(t) = r^{\mathrm{G}} L^{\mathrm{G}}(t-1) - \bar{r}(t) D_k(t-1). \tag{59}$$

The central bank's equity $E^{\mathrm{CB}}(t)$ evolves according to its profits or losses and its past equity and is given by

$$E^{\mathrm{CB}}(t) = E^{\mathrm{CB}}(t-1) + \Pi^{\mathrm{CB}}(t). \tag{60}$$

The net creditor/debtor position of the national economy to the rest of the world $(L^{\mathrm{RoW}}(t))$[24] evolves according to the following law of motion:

$$L^{\mathrm{RoW}}(t) = L^{\mathrm{RoW}}(t-1) + \underbrace{(1+\tau^{\mathrm{EXPORT}}) \sum_l C_l(t)}_{\text{Exports}} - \underbrace{\sum_m P_m(t) Q_m(t)}_{\text{Imports}}, \tag{61}$$

where $\sum_l C_l(t)$ is realized final consumption by foreign consumers (eq. (93)) and $\sum_m P_m(t)Q_m(t)$ are nominal imports (eqs. (84) and (85)), for details see Appendix A.6. Here, for example, a balance of trade surplus (deficit) enters with a negative (positive) sign, since $L^{\mathrm{RoW}}(t)$ is on the asset side of the CB's balance sheet. Thus a trade surplus (deficit), i.e., an inflow (outflow) of money into (out of) the national economy, would reduce (increase) national liabilities versus the RoW. Inherent stock-flow consistency relating to the accounting principles incorporated into our model implies that our financial system is closed via the accounting identity that connects the change in the amount of deposits in the banking system[25] to the government deficit (surplus)[26] and to the balance of trade[27]:

[24] If $L^{\mathrm{RoW}}(t) < 0$, the national economy is a net creditor of the RoW; if $L^{\mathrm{RoW}}(t) > 0$, the national economy is a net debtor to the RoW.

[25] These changes in the amount of deposits in the banking system directly correspond to changes in net central bank reserves $D_k(t)$, which in turn depend the private sector's surplus or deficit in relation to both the government and the RoW.

[26] Financial flows relating to a deficit (surplus) on the part of the government sector either accrue to (are paid by) the private sector (households and firms), or have to flow to (in from) the RoW, in the first case by increasing (decreasing) deposits, and in the second case by increasing (decreasing) D^{ROW}.

[27] A positive (negative) balance of trade will either increase (decrease) deposits held by the private sector, or reduce (increase) the amount of government debt by, e.g., reducing (increasing) the amount of government deficit.

$$E^{\mathrm{CB}}(t)-L^{\mathrm{RoW}}(t)=L^{\mathrm{G}}(t)-D_k(t) \\ =L^{\mathrm{G}}(t)-\sum_{i=1}^{I}D_i(t)-\sum_{h=1}^{H}D_h(t)-E_k(t)+\sum_{i=1}^{I}L_i(t). \tag{62}$$

A.4. Fiscal policy

The government sector is modeled after a large welfare state. Effectively, in our model, the government takes two functions: as a consumer on the retail market (government consumption), and as a re-distributive entity that levies taxes and social contributions to provide social services and benefits to its citizens. We assume that government consumption is exogenous and attributed to individual government entities. Government expenditures, revenues, the deficit, and the public debt, however, are accounted for at the aggregate level (i.e., for the general government).

A.4.1. Government expenditure

Individual government entities j $(j=1,2,\dots,J)$ participate in the goods market as consumers. These entities represent the central government, state government, local governments, and social security funds. The growth rate of real final consumption expenditure of the general government ($C^{\mathrm{G}}(t)$) is assumed to follow an autoregressive process of lag order one (AR(1)):

$$\gamma^{G}(t)=\alpha^{\gamma,\mathrm{G}}\gamma^{\mathrm{G}}(t-1)+\beta^{\gamma,\mathrm{G}}+\epsilon^{\gamma,\mathrm{G}}(t-1), \tag{63}$$

where $\epsilon^{\gamma,\mathrm{G}}(t-1)$ is a random shock with zero mean and variance that takes the extent to which the shocks are common to the other exogenous variables, as reflected by the covariance matrix C, into account, so that

$$C^{\mathrm{G}}(t)=C^{\mathrm{G}}(t-1)\mathrm{e}^{\gamma^{G}(t)}. \tag{64}$$

Similarly, the government's expected growth of prices is defined as

$$\pi^{G}(t)=\alpha^{\pi,\mathrm{G}}\pi^{\mathrm{G}}(t-1)+\beta^{\pi,\mathrm{G}}+\epsilon^{\pi,\mathrm{G}}(t-1), \tag{65}$$

where $\epsilon^{\pi,\mathrm{G}}(t-1)$ is again a random shock with zero mean and variance that takes the extent to which the shocks are common to the other exogenous variables, as reflected by the covariance matrix C, into account. Thus, the government price index evolves in the following manner:

$$P^{\mathrm{G}}(t)=P^{\mathrm{G}}(t-1)\mathrm{e}^{\pi^{G}(t)}. \tag{66}$$

The total nominal government consumption demand is then uniformly distributed to the J government entities and attributed to goods g:

$$C_j^{\mathrm{d}}(t)=\frac{C^{\mathrm{G}}(t)\sum_g c_g^{\mathrm{G}}\bar{P}_g(t-1)(1+\pi^{\mathrm{e}}(t))}{J}, \tag{67}$$

and the consumption budget of the j-th government entity to purchase the g-th good is given by

$$C_{jg}^{\mathrm{d}}(t)=\frac{c_g^{\mathrm{G}}\bar{P}_g(t-1)}{\sum_g c_g^{\mathrm{G}}\bar{P}_g(t-1)}C_j^{\mathrm{d}}(t), \tag{68}$$

where c_g^{G} is the fraction of goods of type g demanded by the government. Realized government consumption is then another outcome of the search-and-matching process on the consumption goods market:

$$C_j(t)\begin{cases}=\sum_g C_{jg}^{\mathrm{d}}(t) & \text{if the government successfully realized the consumption plan, and}\\ <\sum_g C_{jg}^{\mathrm{d}}(t) & \text{if all firms visited could not satisfy its demand.}\end{cases} \tag{69}$$

Other expenditures of the general government include interest payments, social benefits other than social transfers in kind, and subsidies. Interest payments by the general government are made with a fixed average interest rate r^{G} on loans taken out by the government $L^{\mathrm{G}}(t-1)$. Social transfers by the government consist of social benefits for inactive households ($\sum_{h\in H^{\mathrm{inact}}} sb^{\mathrm{inact}}$) such as pension payments or social exclusion benefits, social benefits for any household h ($\sum_h sb^{\mathrm{other}}$) such as relating to family, sickness, or housing, and unemployment benefits for unemployed households ($\sum_{h\in H^{\mathrm{U}}(t)} w_h(t)$). Subsidies are paid to firms with subsidy rates (uniform for each industry, but different across industries) on products and production and are incorporated in the net tax rates on products (τ_i^{Y}) and production (τ_i^{K}), respectively.[28]

[28] The latter can therefore also have negative values if a sector receives more subsidies on products or production than it has to pay in taxes.

A.4.2. Government revenues

Revenues of the general government are generated through taxes, social contributions, and other transfers from all sectors:

$$\begin{aligned} Y^{\mathrm{G}}(t) = {} & \underbrace{(\tau^{\mathrm{SIF}}+\tau^{\mathrm{SIW}})\bar{P}^{\mathrm{HH}}(t)\sum_{h\in H^{\mathrm{E}}(t)} w_h(t)}_{\text{Social security contributions}} + \underbrace{\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\bar{P}^{\mathrm{HH}}(t)\sum_{h\in H^{\mathrm{E}}(t)} w_h(t)}_{\text{Labor income taxes}} \\ & + \underbrace{\tau^{\mathrm{VAT}}\sum_h C_h(t)}_{\text{Value added taxes}} + \underbrace{\tau^{\mathrm{INC}}(1-\tau^{\mathrm{FIRM}})\theta^{\mathrm{DIV}}\left(\sum_i \max(0,\Pi_i(t))+\max(0,\Pi_k(t))\right)}_{\text{Capital income taxes}} \\ & + \underbrace{\tau^{\mathrm{FIRM}}\left(\sum_i \max(0,\Pi_i(t))+\max(0,\Pi_k(t))\right)}_{\text{Corporate income taxes}} + \underbrace{\tau^{\mathrm{CF}}\sum_h I_h(t)}_{\text{Taxes on capital formation}} + \underbrace{\sum_i \tau_i^{\mathrm{Y}} P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on products}} \\ & + \underbrace{\sum_i \tau_i^{\mathrm{K}} P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on production}} + \underbrace{\tau^{\mathrm{EXPORT}}\sum_l C_l(t)}_{\text{Export taxes}}. \end{aligned} \tag{70}$$

A.4.3. Government deficit

The government deficit (or surplus) resulting from its redistributive activities is

$$\begin{aligned} \Pi^{\mathrm{G}}(t) = {} & \underbrace{\sum_{h\in H^{\mathrm{inact}}} \bar{P}^{\mathrm{HH}}(t)sb^{\mathrm{inact}} + \sum_{h\in H^{\mathrm{U}}(t)} \bar{P}^{\mathrm{HH}}(t)\theta^{\mathrm{UB}} w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right) + \sum_h \bar{P}^{\mathrm{HH}}(t)sb^{\mathrm{other}}}_{\text{Social benefits and transfers}} \\ & + \underbrace{\sum_j C_j(t)}_{\text{Government consumption}} + \underbrace{r^{\mathrm{G}} L^{\mathrm{G}}(t-1)}_{\text{Interest payments}} - \underbrace{Y^{\mathrm{G}}(t)}_{\text{Government revenues}}. \end{aligned} \tag{71}$$

A.4.4. Government debt

The government debt as a stock variable is determined by the year-to-year deficits/surpluses of the government sector:

$$L^{\mathrm{G}}(t) = L^{\mathrm{G}}(t-1) + \Pi^{\mathrm{G}}(t). \tag{72}$$

For reasons of model parsimony, we assume that the government sells its debt contracts to the central bank.

A.5. Financial system

For reasons of simplicity we assume that there is one representative financial intermediary for the Canadian economy.[29] The representative bank takes deposits from households and firms, extends loans to firms, and receives advances from (or deposits reserves at) the central bank. The interest rates for loans are set by a fixed markup on the policy rate. Capital of the banking sector grows or shrinks according to bank profits or losses and the write-off of bad debt. The bank is subject to macroprudential policies on both leverage and bank capital. Provision of loans is conditional on a minimum loan-to-value (LTV) ratio, and credit creation is limited by minimum capital requirements.

A.5.1. Provision of loans

The bank extends loans to firms according to a risk assessment of potential borrowers and is subject to a maximum LTV ratio and a minimum capital requirement imposed by the regulator. The bank has imperfect knowledge of the realized value of either its own equity capital or loans extended to the individual firm i. Similar to households and firms, the bank uses heuristics by forming expectations of equity capital ($E_k^{\mathrm{e}}(t)$) and loans as follows: ($\sum_{i=1}^{I}(L_i^{\mathrm{e}}(t)+\Delta L_i(t))$):

[29] This assumption of one representative bank is above all due to national accounting conventions. From national annual sector accounts, which determine the logic of financial flows between the aggregate sectors for our model (households, non-financial corporations, financial corporations, government, and the rest of the world), we obtain balance sheet positions (credit and debt) as well as interest payment flows between firms and the financial sector (banks) on an aggregate level. Since we do not have information on financial relations between individual firms (or industry sectors) and banks for this model, we have no empirically based method to determine credit and debt relations, acquisition and provision of credit, as well as interest payments, between individual firms (or industry sectors) and individual banks. Therefore, we account for credit relations and financial flows between individual firms and banks on an aggregate level for the banking sector, i.e., we assume a representative bank extending credit to individual firms according to the amount of firms' real capital stock, while we account for the value added generated by financial corporations in the real economy according to the logic of input-out tables as separate industries within the firm sector.

$$\frac{E_k^{e}(t)}{\sum_{i=1}^{I}(L_i^{e}(t)+\Delta L_i(t))}=\frac{E_k(t-1)}{\sum_{i=1}^{I}((1-\theta)L_i(t-1)+\Delta L_i(t))}\geq\zeta, \tag{73}$$

where $0<\zeta<1$ is a minimum capital requirement coefficient with $1/\zeta$ representing the maximum allowable leverage. $\Delta L_i(t)$ is the realized new loans to firm i in period t, which is equivalent to the new credit demanded by firms ($\Delta L_i^{d}(t)$, see Equation (46)) if the bank capital requirements are met and the firm borrows within the maximum LTV (see Equation (74) and Equation (75)). When bank capital and leverage requirements are not met, no lending can take place.

Furthermore, the bank forms a risk assessment of a potential default on the part of firm i before granting a loan. This risk assessment is based on the borrower's leverage as measured by its LTV, i.e., the ratio of market value of loans over its capital stock. The bank will grant a loan to firm i only up to the point where the borrower's LTV ratio remains below a regulated maximum level at ζ^{LTV}. However, due to uncertainty, the bank has to form expectations of the value of firm i's capital stock ($K_i^{e}(t)$):

$$\frac{L_i^{e}(t)+\Delta L_i(t)}{K_i^{e}(t)}=\frac{\overbrace{(1-\theta)L_i(t-1)}^{=L_i^{e}(t)}+\Delta L_i(t)}{\underbrace{\bar{P}^{\mathrm{CF}}(t-1)\left(1+\pi^{e}(t)\right)K_i(t-1)}_{=K_i^{e}(t)}}\leq\zeta^{\mathrm{LTV}}, \tag{74}$$

where $K_i^{e}(t)$ denotes firm i's amount of available collateral and $L_i^{e}(t)$ the amount of outstanding debt. The amount of new credit extended to firm i by the bank ($\Delta L_i(t)$) depends on the firm's credit demand, the bank's risk assessment regarding its own capital adequacy, and the leverage of firms requesting the loans:

$$\Delta L_i(t)\begin{cases}=\Delta L_i^{d}(t) & \text{if the borrower's loan-to-value ratio (eq. (74))}\\ & \text{and capital requirements (eq. (73)) are satisfied}\\ <\Delta L_i^{d}(t) & \text{otherwise.}\end{cases} \tag{75}$$

The order of arrival of firms at the bank is assumed to be random. A financially robust (low leverage) firm, which in principle deserves a large chunk of bank loans, may be denied credit if it arrives "too late" (i.e., after other less robust firms).

A.5.2. Banks' balance sheets

The bank's profits are computed as the difference between interest revenues from loans provisions (including overdrafts on deposit accounts incurred by firms and households ($D_{i,h}(t-1)<0$)) and costs due to interest payments on deposits held with the bank by firms and households ($D_{i,h}(t-1)>0$):

$$\begin{aligned}\Pi_k(t)=&\underbrace{r(t)\left(\sum_{i=1}^{I}L_i(t-1)+\max(0,-D_i(t-1)\right)+r(t)\sum_{h=1}^{H}\max(0,-D_h(t-1))+\bar{r}(t)\max(0,D_k(t-1))}_{\text{Interest received}}\\&\underbrace{-\bar{r}(t)\sum_{i=1}^{I}\max(0,D_i(t-1))-\bar{r}(t)\sum_{h=1}^{H}\max(0,D_h(t-1))-\bar{r}(t)\max(0,-D_k(t-1))}_{\text{Interest payments}}\end{aligned} \tag{76}$$

Deposits are remunerated at the policy rate $\bar{r}(t)$, which we assume to be set exogenously by the central bank.[30] The effective interest rate $r(t)$ faced by firms for bank credit is determined by a fixed markup μ over the policy rate $\bar{r}(t)$:

$$r(t)=\bar{r}(t)+\mu. \tag{77}$$

Bank equity evolves according to bank profits or losses and is given by

$$\begin{aligned}E_k(t)=&E_k(t-1)+\Pi_k(t)-\underbrace{\theta^{\mathrm{DIV}}(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_k(t))}_{\text{Dividend payments}}\\&\underbrace{-\tau^{\mathrm{FIRM}}\max(0,\Pi_k(t))}_{\text{Corporate taxes}}-\underbrace{\sum_{i\in I'}(L_i(t)-D_i(t)-\zeta^{b}\bar{P}_i^{\mathrm{CF}}(t)K_i(t)),}_{\text{Write-off of bad debt}}\end{aligned} \tag{78}$$

where I' is the set of insolvent borrowers, and we assume that outstanding overdraft of firm i's deposit account as well as a fraction $(1-\zeta^{b})\bar{P}_i^{\mathrm{CF}}(t)K_i(t)$ of loans extended to firm i have to be written off from the bank's balance sheet. The bank's balance sheet includes

[30] For simplicity, we abstract from modeling the ELB in this version. We are currently working on an extension to consider the implications of extended monetary policy when incorporating the ELB.

(1) loans to firms (on the asset side); (2) deposits received (on the liability side), (3) equity capital; and (4) (net) central bank reserves held, $D_k(t)$, or advances obtained by the bank from the central bank[31]:

$$D_k(t) = \sum_{i=1}^{I} D_i(t) + \sum_{h=1}^{H} D_h(t) + E_k(t) - \sum_{i=1}^{I} L_i(t). \tag{79}$$

A.6. Foreign linkages

Foreign linkages of CANVAS are introduced in the form of trade linkage as in the Bank of Canada's main DSGE model, ToTEM (Corrigan et al., 2021). We simplify the modeling of the foreign economy by assuming one representative foreign firm in each sector supplies Canadian imported goods (raw materials, capital, and consumption goods). We also assume homogeneous consumers in the foreign economy who demand Canadian exports. Similar to ToTEM, we assume the foreign demand for Canadian exports and the supply of foreign goods to be exogenously given, since Canada is a small open economy. Canadian demand for imports is endogenous and is subject to supply constraint.

A.6.1. Imports

We model, at the individual firm level, the Canadian economy as an open economy where a segment of the firm's sector participates in international trade. The growth rate of the supply of imports ($Y^{\mathrm{I}}(t)$) is assumed to follow an autoregressive process of lag order one (AR(1)):

$$\gamma^{\mathrm{I}}(t) = \alpha^{\gamma,\mathrm{I}}\gamma^{\mathrm{I}}(t-1) + \beta^{\gamma,\mathrm{I}} + \epsilon^{\gamma,\mathrm{I}}(t-1), \tag{80}$$

where $\epsilon^{\gamma,\mathrm{I}}(t-1)$ is a random shock with zero mean. This means that the total supply of imports evolves in the following manner:

$$Y^{\mathrm{I}}(t) = Y^{\mathrm{I}}(t-1)\mathrm{e}^{\gamma^{\mathrm{I}}(t)}. \tag{81}$$

A representative foreign firm for each sector imports goods from the rest of the world and supplies them to domestic markets. Thus the m-th, $(m = 1, 2, \dots, S)$, foreign firm representing an industry s imports the principal product g[32]:

$$Y_m(t) = c^{I}_{g=s} Y^{\mathrm{I}}(t), \tag{82}$$

where $c^{I}_{g=s}$ is the fraction of imported goods of type g as part of total imports.

As in Equation (81), import price growth also follows an AR(1) process:

$$\pi^{\mathrm{I}}(t) = \alpha^{\pi,\mathrm{I}}\pi^{\mathrm{I}}(t-1) + \beta^{\pi,\mathrm{I}} + \epsilon^{\pi,\mathrm{I}}(t-1), \tag{83}$$

where $\epsilon^{\pi,\mathrm{I}}(t-1)$ is again a random shock with zero mean and estimated variance. Import price is determined exogenously:

$$P_m(t) = P_m(t-1)\mathrm{e}^{\pi^m(t)}. \tag{84}$$

Sales of imports are then the realized demand as an outcome of the search-and-matching process on the goods markets (i.e., the minimum amount of import demand that can satisfy import supply, and vice versa):

$$Q_m(t) = \min(Y_m(t), Q^d_m(t)), \tag{85}$$

where $Q^{\mathrm{d}}_m(t)$ is subject to the search-and-matching mechanism specifying the demand by consumers from foreign firm m:

$$Q^{\mathrm{d}}_m(t) \begin{cases} < Y_m(t) & \text{if demand from consumers is smaller than supply from foreign firm } m, \\ = Y_m(t) & \text{if demand from consumers exactly matches supply from foreign firm } m, \text{ and} \\ > Y_m(t) & \text{if demand from consumers is larger than supply from foreign firm } m. \end{cases} \tag{86}$$

A.6.2. Exports

The l-th (l = 1, 2, . . . , L) foreign agent, be it a foreign firm, household, or government entity, participates in the domestic goods market as a consumer. Total sales to these foreign consumers on domestic markets represent exports to the rest of the world. Analogous to imports, the growth rate of the total demand for exports ($C^{\mathrm{E}}(t)$) is assumed to follow an autoregressive process of lag order one (AR(1)):

[31] A positive net central bank reserve ($D_k(t) > 0$) implies the bank holds more central bank reserves than advances and is thus a net creditor to the central bank. In contrast, a negative net central bank reserve ($D_k(t) < 0$) implies that the bank is a net debtor to the central bank. The possibility of an inequality of advances and reserves, or, for that matter, an inequality of loans and deposits, is due to the fact that we do not explicitly distinguish between deposits and reserves for reasons of model parsimony. Rather, we use the central bank as a "clearing house" for flows of reserves and deposits between the national economy and the foreign economy (see Equation (62)).

[32] As for domestic firms, we suppose there is a one-to-one correspondence between the sets of industries s and products g, meaning that the n-th sector produces only the n-th good, and $S = G$.

$$\gamma^{\mathrm{E}}(t)=\alpha^{\gamma,\mathrm{E}}\gamma^{\mathrm{E}}(t-1)+\beta^{\gamma,\mathrm{E}}+\epsilon^{\gamma,\mathrm{E}}(t-1), \tag{87}$$

where $\epsilon^{\gamma,\mathrm{E}}(t-1)$ is a random shock with zero mean. Total demand for exports thus becomes:

$$C^{\mathrm{E}}(t)=C^{\mathrm{E}}(t-1)\mathrm{e}^{\gamma^{\mathrm{E}}(t)}. \tag{88}$$

The growth rate of export prices is analogous to Equation (87):

$$\pi^{\mathrm{E}}(t)=\alpha^{\pi,\mathrm{E}}\pi^{\mathrm{E}}(t-1)+\beta^{\pi,\mathrm{E}}+\epsilon^{\pi,\mathrm{E}}(t-1), \tag{89}$$

where $\epsilon^{\pi,\mathrm{E}}(t-1)$ is again a random shock with zero mean. Thus, the export price index is determined exogenously:

$$P^{\mathrm{E}}(t)=P^{\mathrm{E}}(t-1)\mathrm{e}^{\pi^{\mathrm{E}}(t)}. \tag{90}$$

Total demand for exports is uniformly distributed to L foreign consumers and attributed to good g. The demand for exported goods by the l-th foreign consumer is

$$C_l^d(t)=\frac{P^{\mathrm{E}}(t)\cdot C^{\mathrm{E}}(t)}{L} \tag{91}$$

and the demand for exports by the l-th foreign consumer to purchase the g-th good is given by

$$C_{lg}^{\mathrm{d}}(t)=\frac{c_g^{\mathrm{E}}\bar{P}_g(t-1)}{\sum_g c_g^{\mathrm{E}}\bar{P}_g(t-1)}C_l^{\mathrm{d}}(t) \tag{92}$$

where $c_g^{\mathrm{E}}(t)$ is the fraction of exports of type g goods.

Final realized consumption by foreign consumers is an outcome of the search-and-matching process on the goods market:

$$C_l(t)\begin{cases}=\sum_g C_{lg}^d(t) & \text{if the foreign consumer successfully realized the consumption plan, and}\\ <\sum_g C_{lg}^d(t) & \text{if none of Canadian exporting firms visited could satisfy its demand.}\end{cases} \tag{93}$$

A.7. Macroeconomic aggregates

GDP in the model can be calculated by aggregating the value of all final goods and services produced and purchased by agents in the model in a given period. The nominal GDP and its components of each period t can be defined by three different approaches: (1) production; (2) expenditure based, and (3) income based:

$$\begin{aligned}
GDP(t)=&\underbrace{\sum_i \tau_i^{\mathrm{Y}}P_i(t)Y_i(t)+\sum_h \tau^{\mathrm{VAT}}C_h(t)+\sum_h \tau^{\mathrm{CF}}I_h(t)+\sum_j \tau^{\mathrm{G}}C_j(t)+\sum_l \tau^{\mathrm{EXPORT}}C_l(t)}_{\text{Taxes on products}}\\
&+\underbrace{\sum_i(1-\tau_i^{\mathrm{Y}})P_i(t)Y_i(t)}_{\text{Total sales of goods and services}}-\underbrace{\sum_i\frac{1}{\beta_i}\bar{P}_i(t)Y_i(t)}_{\text{Intermediate inputs}}\quad\text{(Production approach)}\\
=&\underbrace{\sum_h(1+\tau^{\mathrm{VAT}})C_h(t)}_{\text{Household consumption}}+\underbrace{\sum_j(1+\tau^{\mathrm{G}})C_j(t)}_{\text{Government consumption}}+\underbrace{\sum_h(1+\tau^{\mathrm{CF}})I_h(t)+\sum_i P_i^{\mathrm{CF}}(t)I_i(t)}_{\text{Gross fixed capital formation}}\\
&+\underbrace{\sum_i P_i(t)(Y_i(t)-Q_i(t))+\bar{P}_i(t)\left(\Delta M_i(t)-\frac{1}{\beta_i}Y_i(t)\right)}_{\text{Changes in inventories}}\\
&+\underbrace{\sum_l(1+\tau^{\mathrm{EXPORT}})C_l(t)}_{\text{Exports}}-\underbrace{\sum_m P_m(t)Q_m(t))}_{\text{Imports}}\quad\text{(Expenditure approach)}\\
=&\underbrace{\sum_i \tau_i^{\mathrm{Y}}P_i(t)Y_i(t)+\sum_h \tau^{\mathrm{VAT}}C_h(t)+\sum_h \tau^{\mathrm{CF}}I_h(t)+\sum_j \tau^{\mathrm{G}}C_j(t)+\sum_l \tau^{\mathrm{EXPORT}}C_l(t)}_{\text{Taxes on products}}\\
&+\underbrace{\sum_i P_i(t)Y_i(t)-(1+\tau^{\mathrm{SIF}})\bar{P}^{\mathrm{HH}}(t)N_i(t)w_i(t)-\frac{1}{\beta_i}\bar{P}_i(t)Y_i(t)-\tau_i^{\mathrm{Y}}P_i(t)Y_i(t)-\tau_i^{\mathrm{K}}P_i(t)Y_i(t)}_{\text{Gross operating surplus and mixed income}}
\end{aligned} \tag{94}$$

$$+\underbrace{\sum_i (1+\tau^{\mathrm{SIF}})\bar{P}^{\mathrm{HH}}(t)N_i(t)w_i(t)}_{\text{Compensation of employees}}+\underbrace{\sum_i \tau_i^{\mathrm{K}}P_i(t)Y_i(t)}_{\text{Net taxes on production}} \quad \text{(Income approach)}$$

The GDP deflator is the economy-wide average producer price of all goods and services produced and sold, where all individual prices and sales are determined on the agent level by our search-and-matching mechanism. In our model, the GDP deflator is defined as nominal GDP divided by real GDP:

$$GDP\ deflator(t)=\frac{GDP(t)}{real\ GDP(t)}, \tag{95}$$

where

$$\begin{aligned} real\ GDP(t) &= \sum_i \tau_i^{\mathrm{Y}}Y_i(t)+\sum_h \tau^{\mathrm{VAT}}\frac{C_h(t)}{\bar{P}_h(t)}+\sum_h \tau^{\mathrm{CF}}\frac{I_h(t)}{\bar{P}_h^{\mathrm{CF}}(t)}+\sum_j \tau^{\mathrm{G}}\frac{C_j(t)}{\bar{P}_j(t)} \\ &+\sum_l \tau^{\mathrm{EXPORT}}\frac{C_l(t)}{\bar{P}_l(t)}+\sum_i (1-\tau_i^{\mathrm{Y}})Y_i(t)-\sum_i \frac{1}{\beta_i}Y_i(t). \end{aligned} \tag{96}$$

Appendix B. Additional details on initial conditions for the Canadian economy

This appendix presents details on the initial conditions for the Canadian economy. In Tables 6 and 7, we show, as an example, initial conditions for 2019:Q4.

B.1. The central bank

Initial central bank's equity ($E^{\mathrm{CB}}(0)$) is the residual on the central bank's passive side, obtained by deducting initial bank reserves held ($D_k(0)$) and the initial net creditor/debtor position with the rest of the world ($D^{\mathrm{RoW}}(0)$) from the central bank's assets (initial government debt ($L^{\mathrm{G}}(0)$)). Thus, the initial central bank's equity ($E^{\mathrm{CB}}(0)$) is set according to Equation (62) where the initial balance of trade with the rest of the world ($D^{\mathrm{RoW}}(0)$) is assumed to be zero and the initial bank reserves held ($D_k(0)$) are set according to Equation (79).

B.2. The general government

Initial government debt ($L^{\mathrm{G}}(0)$) is set according to the Canadian government's consolidated gross debt.

B.3. The financial system

The initial bank's equity ($E_k(0)$) is obtained from national accounting data, and the initial bank's profits are given by the initial income from interest less interest payments:

$$\Pi_k(0)=\mu\sum_i L_i(0)+\bar{r}(0)E_k(0),$$

Table 6
Initial conditions.

Initial condition	Description	Value
$P_i(0)$	Initial price of the i^{th} firm	initial conditions are firm (i) and household (h) specific
$Y_i(0)/Q_i^{\mathrm{d}}(0)$	Initial production/demand of the i^{th} firm (in mln. CAD)	
$K_i(0)$	Initial capital of the i^{th} firm (in mln. CAD)	
$M_i(0)$	Initial stocks of raw materials, consumables, supplies of the i^{th} firm (in mln. CAD)	
$S_i(0)$	Initial stocks of finished goods of the i^{th} firm (in mln. CAD)	
$N_i(0)$	Initial number of employees of the i^{th} firm	
$D_i(0)$	Initial liquidity (deposits) of the i^{th} firm (in mln. CAD)	
$L_i(0)$	Initial debt of the i^{th} firm (in mln. CAD)	
$\Pi_i(0)$	Initial profits of the i^{th} firm (in mln. CAD)	
$D_h(0)$	Initial personal assets (deposits) of the h^{th} household (in mln. CAD)	
$K_h(0)$	Initial household capital (in mln. CAD)	
$w_h(0)$	Initial wage of the h^{th} household (in mln. CAD)	
$L^{\mathrm{G}}(0)$	Initial government debt (in mln. CAD)	2658545
$\Pi_k(0)$	Initial banks' profits (in mln. CAD)	bank-specific
$E_k(0)$	Initial banks' equity (in mln. CAD)	593541
$E^{\mathrm{CB}}(0)$	Initial central banks' equity (in mln. CAD)	1879086
$L^{\mathrm{RoW}}(0)$	Initial net creditor/debtor position of the national economy to RoW (in mln. CAD)	0

Note: Initial conditions are shown for 2019:Q4.

Table 7
Initial conditions for the institutional sectors.

Initial condition	Description	Value
D^{I}	Initial liquidity (deposits) of the firm sector (in mln. CAD)	560984
L^{I}	Initial debt of the firm sector (in mln. CAD)	1937189
ω	Desired capacity utilization rate	0.85
w^{UB}	Initial unemployment benefits (in mln. CAD)	0.2839
D^{H}	Initial personal assets (deposits) of the household sector (in mln. CAD)	1562123
K^{H}	Initial capital (dwellings) of the household sector (in mln. CAD)	3314388

Note: Initial conditions are shown for 2019:Q4.

where initial advances from the central bank ($D_k(0)$) are set according to Equation (79).

Data availability

Data will be made available on request.

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